



Development of Novel Microenvironments for Promoting Enhanced Wound Healing

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Abstract

Purpose of Review Non-healing wounds are a significant issue facing the healthcare industry. Materials that modulate the wound microenvironment have the potential to improve healing outcomes.

Recent Findings A variety of acellular and cellular scaffolds have been developed for regulating the wound microenvironment, including materials for controlled release of antimicrobials and growth factors, materials with inherent immunomodulative properties, and novel colloidal-based scaffolds. Scaffold construction methods include electrospinning, 3D printing, decellularization of the extracellular matrix, or a combination of techniques. Material application methods include layering or injecting at the wound site.

Summary Though these techniques show promise for repairing wounds, all material strategies thus far struggle to induce regeneration of features such as sweat glands and hair follicles. Nonetheless, innovative technologies currently in the research phase may facilitate future attainment of these features. Novel methods and materials are constantly arising for the development of microenvironments for enhanced wound healing.

Keywords Wound microenvironment · Wound modulation · Chronic wounds · Biomaterials · Biomaterials for wound healing · Novel wound healing materials

Introduction

Degenerative non-healing wounds are a significant issue in the medical industry. A retrospective study of chronic wounds using data collected in 2014 determined that 14.5% of Medicare beneficiaries in the USA, or 8.2 million patients, were diagnosed with at least one wound or wound-related infection. This resulted in an average annual wound care cost of \$2.4 billion and a midrange healthcare cost estimate of \$31.7 billion that year [1, 2]. In an effort to repair damaged dermal tissue, healthcare providers desire wound dressings,

artificial skin substitutes, or alternative means of protecting the wound from infection while enhancing the body's natural wound-healing mechanisms. For this reason, several strategies for wound repair have been developed, including controlled release materials for antimicrobial and growth factor delivery, various hydrogels and scaffolds produced via electrospinning and 3D printing, materials derived from cell-extracellular membranes, and nanomaterial and colloidal approaches. In this review, we discuss the wound healing cascade and methods by which biomaterials can be used to modulate the wound microenvironment. We additionally describe traditional and emergent materials used to enhance the natural wound healing process.

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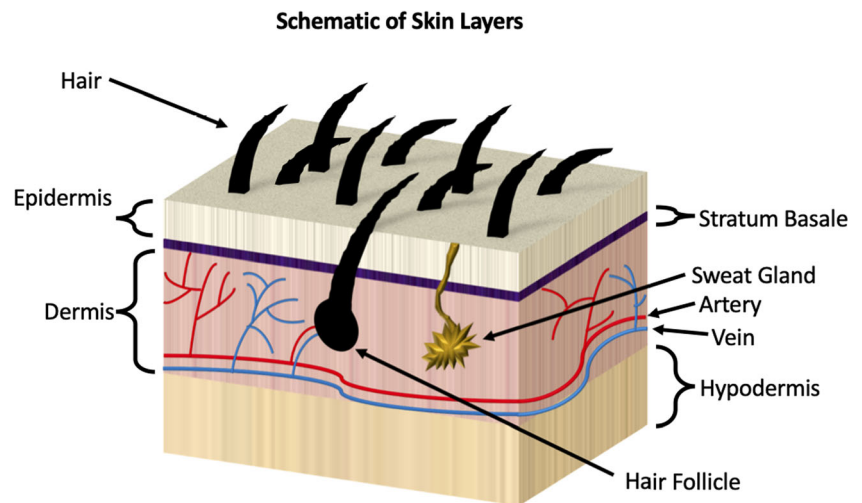
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Introduction to Skin Physiology and the Wound Healing Process

The skin is composed of three sections arranged in order from exterior to interior: the epidermis, dermis, and hypodermis (Fig. 1). The epidermis is the protective outer barrier primarily formed from keratinocytes, which are cells that range from

Fig. 1 Schematic of the major skin layers, including the epidermis, basement membrane, dermis, and hypodermis



cuboidal to flattened in shape and are tightly packed. This layer is stratified into four sections from exterior to interior: the stratum corneum, stratum granulosum, stratum spinosum, and stratum basale. Once keratinocyte progenitor cells differentiate in the stratum basale, keratinocytes continue to progress outwards through the layers as they mature until cell death occurs in the stratum corneum, where the cells become the body's protective exterior layer [3, 4, 5–7]. The dermal layer determines the mechanical properties of the skin and is comprised primarily of extracellular matrix (ECM), the fibroblast cells which secrete the ECM and growth factors, and immune cells. It is divided into the papillary, subpapillary, and reticular layers, and is separated from the epidermis by a basement membrane [4, 5, 7–10]. The hypodermis is composed of adipocyte cells in a fatty layer and is primarily used for cushioning and insulation of the body [4, 8, 11]. Upon injury, the structural integrity of the skin is compromised and must be repaired via the wound healing process.

Any breach in the skin barrier necessitates wound healing. While damaged tissue from acute punctures to the epidermis such as cuts and minor burns can be repaired efficiently, damage to the dermal layer can result in the formation of disorganized scar tissue. Additionally, large or infected dermal abrasions, large burns, ulcers, or certain pathologies that inhibit cell migration such as diabetes can result in the development of chronic non-healing wounds from acute wounds [7, 12, 13]. Typically, wound healing is a process characterized by four stages: hemostasis, inflammation, cell proliferation and reepithelialization, and tissue maturation and remodeling [7, 14]. When there is damage to the skin (Fig. 2), bleeding occurs and the coagulation cascade is activated, promoting primary and secondary hemostasis. Primary hemostasis is the process by which blood flow to the wound area is blocked by a temporary platelet “plug” formed by platelets that are activated by von Willebrand factor (VWF) at injured vessel walls. Platelets are anuclear blood cells derived from bone marrow

megakaryocytes which circulate in an inactive state until activated [15–17]. Once platelets deform and spread along the vascular wall and aggregate to occlude the wound site, secondary hemostasis occurs to create a fibrin-rich clot. During this process, the culmination of the coagulation cascade leads to thrombin enzyme generation/activation: thrombin cleaves fibrinogen into fibrin strands, and fibrin is cross-linked to the platelet “plug” to form a complete clot for hemostasis [16, 17]. Platelet-fibrin interactions play a critical role in determining clot properties and, in turn, the hemostatic and pro-healing properties of the wound microenvironment. Via actin/myosin-generated contractile mechanisms, platelets pull on the fibrin strands in the clot through a process known as clot retraction, which decreases clot surface area, increases clot stability, and promotes blood flow to carry nutrients to the healing tissue [16, 18, 19]. Inflammation also occurs shortly after the injury, overlapping temporally with hemostasis, where immune cells such as neutrophils and macrophages are recruited to clean the wound site of bacteria and debris and secrete growth factors to stimulate the subsequent cell proliferation phase of wound repair [7, 20]. During the cell proliferation phase, fibroblasts from the surrounding tissue are drawn into the clot by macrophage growth factors and secrete ECM, forming replacement connective tissue [4, 21]. Reepithelialization then occurs as fibroblasts, keratinocytes, and other surrounding epithelial cells migrate into the ECM and form rudimentary granulation tissue, while neovascularization simultaneously occurs to provide nutrient and waste transport to the wound site [4, 7, 22–24]. The maturation phase then ensues, where fibroblasts in the granulation tissue differentiate into myofibroblasts, which contract the wound tissue and generate copious quantities of ECM, thereby replacing the predominantly collagen type III matrix with mechanically stronger type I collagen [4, 20].

The myriad processes involved in wound healing provide numerous opportunities to engineer the microenvironment

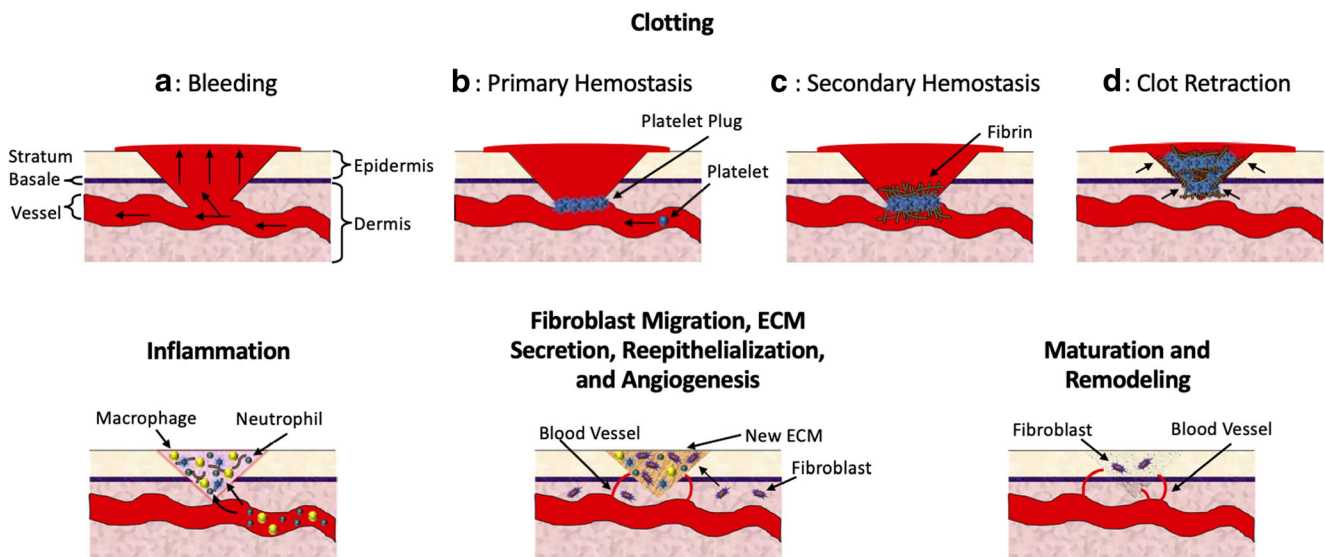


Fig. 2 Schematic of the wound healing process, depicting the stages of clotting, inflammation, fibroblast migration, reepithelialization, and angiogenesis and maturation. These phases overlap temporally to promote repair, replacement, and remodeling of damaged skin tissue. Upon injury, bleeding occurs, and hemostasis follows to stop the bleeding. Primary hemostasis occurs and consists of the formation of a platelet plug to occlude the wound site. Fibrin formed from the cleaving

of fibrinogen by thrombin is cross-linked with the platelet plug to form a more robust clot in secondary hemostasis, and this clot is later retracted by platelets. Subsequently, inflammation occurs to remove pathogens and damaged material from the wound site, and fibroblasts migrate into the clot to secrete ECM while angiogenesis occurs to bring nutrients into the new tissue. Over longer time scales (weeks/months), this new tissue matures and is remodeled by local cells

and promote greater healing efficiency. Materials can be used to introduce growth factors, stem cells, antimicrobial agents, structural ECM, or active ECM modifiers to the wound site [7]. Some materials are also designed to enhance aspects of the wound healing cascade by delivering necessary proteins for thrombus development or replacing components with artificial substitutes. Moderation of wound pH, temperature, oxygen and carbon dioxide composition, microbe and cell content, and hydration are also critical considerations for enhancement of the natural wound healing process [4•]. In subsequent sections, we provide an overview of material-based strategies for engineering the wound microenvironment to promote enhanced healing.

Overview of Biomaterial Strategies for Promoting Wound Repair

Just as there are a vast array of steps in the wound healing process, there are myriad strategies in development to enhance these steps to enable efficient wound microenvironment modulation and improve wound closure rates. These include materials employed for controlled release to prevent infection and promote wound healing, such as hydrogel scaffolds and nanomaterials, and development of means for producing these materials, such as electrospinning, 3D bioprinting, and cell and tissue-derived production. These methods will be detailed in the following sections.

Controlled Release Materials

The human body employs a plethora of bioactive molecules to initiate and regulate the wound healing cascade. Controlled release materials enable the delivery of concentrated doses of these molecules to the wound site at a tunable rate, rather than in a single bolus injection. Proteins such as growth factors facilitate various steps along the wound healing cascade and have been extensively incorporated into controlled-release materials for wound healing. Immunomodulatory and antimicrobial agents have also been incorporated into scaffolds to prevent bacterial proliferation and the formation of biofilms at the wound site and to reduce the immunogenic response elicited by implantation of the therapeutic material [25]. These various controlled release molecules are detailed here.

There are several families of growth factors (Table 1) that have significant effects upon wound healing time and success rates, including epidermal growth factor (EGF), fibroblast growth factor (FGF), transforming growth factor- β (TGF- β), platelet-derived growth factor (PDGF), and vascular endothelial growth factor (VEGF). For the EGF family, primary wound healing proteins include EGF, transforming growth factor- α (TGF- α), and heparin-binding EGF (EGF-HB), all of which bind EGF receptors (EGFRs) to increase keratinocyte migration and proliferation in the wound site [26–30]. The FGF family for wound healing primarily consists of FGF-2, which promotes migration of keratinocytes and fibroblasts and stimulates the production of ECM

Table 1 Growth factors and their effects on wound healing

Growth factor family	Growth factor	Effects	Source
Epidermal growth factor (EGF)	Epidermal growth factor (EGF)	Binds EGF receptors (EGFRs) to increase keratinocyte migration and proliferation in the wound site.	[26–30]
	Transforming growth factor- α (TGF- α)		
	Heparin-binding epidermal growth factor (EGF-HB)		
Fibroblast growth factor (FGF)	Fibroblast growth factor-2 (FGF-2)	Promotes migration of keratinocytes and fibroblasts and stimulates the production of ECM components	[30–34]
	Fibroblast growth factor-7 (FGF-7)	Increases migration and proliferation of keratinocytes and participate in the reduction of harmful reactive oxygen species (ROS) in the wound site.	
	Fibroblast growth factor-10 (FGF-10)		
Transforming growth factor- β (TGF- β)	Transforming growth factor- β 1 (TGF- β 1)	Primary wound healing molecule, has a significant role in hemostasis, angiogenesis, and reepithelialization.	[30, 35, 36]
	Activins	Influences expression of growth factors in dermal fibroblasts and keratinocyte differentiation	[30, 37–39]
	Bone morphogenic proteins (BMPs)		
Platelet-derived growth factor (PDGF)	Platelet-derived growth factor (PDGF)	Stimulates inflammatory cell and fibroblast migration to the wound site upon injury, promotes angiogenesis and vessel maturation, upregulates critical reepithelialization factors, and upregulates collagen remodeling factors	[29, 30, 40–44]
Vascular endothelial growth factor (VEGF)	Vascular endothelial growth factor-A (VEGF-A)	Stimulates angiogenesis via endothelial cell migration and proliferation	[30, 45–47]
	Vascular endothelial growth factor-C (VEGF-C)	Recruits hematopoietic and inflammatory cells to the wound site and stimulates angiogenesis	[30, 48, 49]
	Placental growth factor (PLGF)	Promotes granulation tissue formation, maturation, and vascularization	[50, 51]

components, as well as FGF-7 and FGF-10, which increase migration and proliferation of keratinocytes and participate in the reduction of harmful reactive oxygen species (ROS) in the wound site [30–34]. Within the TGF- β family, TGF- β 1 is the primary wound healing molecule and has a significant role in inflammation, angiogenesis, and reepithelialization [30, 35, 36]. Activins and bone morphogenic proteins (BMPs) are other members of the TGF- β family, which influence the expression of growth factors in dermal fibroblasts and keratinocyte differentiation [30, 37–39]. PDGF has a role in each phase of the wound healing cycle by stimulating inflammatory cell and fibroblast migration to the wound site upon injury, promoting angiogenesis and vessel maturation, upregulating critical reepithelialization factors, and upregulating collagen remodeling factors [29, 30, 40–44]. As for the VEGF family, VEGF-A stimulates angiogenesis via endothelial cell migration and proliferation [30, 45–47], VEGF-C recruits hematopoietic and inflammatory cells to the wound site and stimulates angiogenesis [30, 48, 49], and placental growth factor (PLGF) promotes granulation tissue formation, maturation, and vascularization [50, 51]. In chronic wounds, the concentrations of these factors are decreased with respect to a healthy individual, and their delivery to the wound site is therefore believed to be of potential benefit to a patient [30]. Several methods of

incorporating these growth factors into scaffolds have been proposed to combat half-life and clearance issues, including direct addition of factors during scaffold production, loading of factors in solution into scaffolds via absorption, encapsulating factors into nanoparticles, and conjugating factors to scaffold cross-linkers [52].

Regarding the controlled release of immunoregulatory molecules, popular materials include honey, chitosan, silver nanoparticles and ions, copper, zinc, antibiotics, and antiseptics [7, 53]. Honey has been found to dehydrate bacteria and extract wound exudate, while chitosan interrupts the phospholipid bilayer of the bacterial cell wall, and silver is thought to interrupt the DNA replication process and cause destruction of the bacterial plasma membrane [7, 54–56]. Zinc has demonstrated antibacterial capabilities and promotes keratinocyte migration, while copper promotes fibroblast proliferation [53, 57, 58]. Common antibiotics include minocyclin, vancomycin, ciprofloxacin, and streptomycin, while antiseptics such as chlorhexidine, hydrogen peroxide, and poly(hexamethylene) biguanide hydrochloride (PHMB) are used [53, 59–65]. Often, these molecules are core components of the scaffold itself or loaded into scaffolds via similar means as the growth factors above for direct administration and controlled release into the wound site, where they enact

immunomodulatory, microbicidal, or pro-angiogenic and pro-cell viability effects. At times, combinations of molecules are delivered as a multifaceted approach to combating infection and chronic wounds simultaneously.

Hydrogels

Hydrogels are commonly used scaffolding materials in wound healing that can be directly applied to the wound or in some cases injected into the tissue for self-assembly [4•]. Hydrogels are hydrophilic three-dimensional networks of cross-linked polymers that swell extensively in water, are suitable for use in all stages of the wound healing process, are composed of a large array of bio-inert substances, and are capable of being loaded with controlled-release materials [7, 66]. Hydrogels are formed by cross-linking polymers into a three-dimensional gel matrix through physical or chemical means, which improves their strength, resistance to degradation, and tunability of mechanical properties to the specific environment in which they will be used. Physical cross-linking entails utilizing the polymer's reversible solid-gel transition phase, entangling polymer chains, hydrogen bonding, hydrophobic interaction, and crystallite formation [66, 67]. Chemical cross-linking is non-reversible and involves the covalent binding of the polymers using a cross-linking agent, as well as various other polymerization approaches [7, 67]. Some popular natural polymers for the development of pro-healing hydrogels include alginate, chitosan, gelatin, collagen, hyaluronic acid (HA), and cellulose, while synthetics include polyethylene glycol (PEG), polyvinyl alcohol (PVA), polynipam (pNIPAM), and polystyrene (PS) [16, 66].

Nanomaterials

Nanomaterials, such as nanofibers and nanoparticles, are increasingly popular materials for use in drug delivery and scaffolding for wound repair. Utilizing materials with nanoscale features enables direct material-to-cell interaction mechanisms which may not be possible with larger-scale materials. Scaffolds and particles can be loaded with therapeutic molecules for controlled release approaches [68•].

Nanofibers can be constructed from many of the same materials as hydrogels to obtain natural biodegradable, synthetic, and hybrid characteristics in an effort to mimic ECM in the native tissue environment and exhibit adjustable porosity. The nanofiber physical characteristics and fiber alignment have a distinct impact upon the immune response, angiogenesis in the wound site, and cell viability, proliferation, and migration [68•]. The most common production method for these fibers is the process of electrospinning, where in short, a voltage is generated over a polymeric solution as it is being ejected from

a syringe and forces droplets into a Taylor cone shape and down into a collector, where the polymers are then elongated, dried, cooled, and spun into fibers [7, 69]. Electrospinning enables tight control over fiber alignment and spatial arrangement, and the morphology of the resultant fiber can be edited by adjusting the concentration of the polymer, polymer type(s) used, collector electric field, temperature, and humidity [7, 68–72]. Unlike hydrogels, however, many electrospun nanofiber scaffolds are unable to absorb sufficient quantities of wound exudate and maintain a moist environment conducive to wound healing [7]. Beyond electrospinning, plant and bacterial cellulose fibers and self-assembling peptides can be used as nanofiber materials for wound repair [7]. Despite their organic origin, these forms of cellulose have both been found to not exhibit immunologic effects when utilized as scaffolding material [73, 74].

There are a number of different nanoparticle strategies in development for the delivery of therapeutic molecules into the wound site, with benefits such as controlled and targeted drug delivery, protection of molecules from degradation, decreased toxicity, and easy integration with other wound healing techniques [68, 75]. Nanoparticle types include micelles, self-assembled core-shell structures; polymeric nanoparticles composed of biodegradable polymers; nanoemulsions, nanometric droplets dispersed into another immiscible liquid; liposomes, spherical lipid bilayer structures; cyclodextrins, hollow particles of cyclic oligosaccharides from glucopyranose; and inorganic nanoparticles, composed of metals [68•]. Application of these nanoparticle types in wound healing has been recently reviewed by Alberti et al. [68•]. Beyond use for drug delivery, nanoparticles can be used to recapitulate cellular properties involved in the wound healing cascade, as evidenced by Brown et al.'s platelet-like particles [16].

Some strategies involve hybrid scaffolds that consist of hydrogels and microparticles in combination [76••]. For instance, scaffolds have been developed that are composed of microgels cross-linked together to form highly degradable, injectable scaffolds. Zhou et al. investigated this idea by mixing degradable PEG-lactic acid microgels with non-degradable PEG microgels in multiple ratios for injection, self-assembly into a scaffold, and tunable degradation. Microgels were fabricated at 100%, 75%, 50%, 25%, and 0% biodegradability and characterized to find that a higher biodegradable polymer composition degrades faster, fibroblasts encapsulated in the gels during the production process experienced roughly the same viability in each scaffold at 14 days, and that a slower degradation rate improved cell proliferation *in vitro* [77]. Riley et al. discuss injectable hydrogel microparticles (HMPs) which jam above a specific packing fraction into a bulk product, forming a granular scaffold. HMPs having a diameter greater than 10 μm and a packing fraction of 0.58 self-assemble into these granular hydrogels, which switch from a liquid to a solid once injected

and are not required to gel or cross-link *in vivo* [78]. Darling et al. demonstrate this process using injectable, HA-based spatially patterned hydrogel microparticles. The granular gel had adjustable layering and orientation capabilities *in vitro* and *in vivo* post-injection, and researchers discovered that layering gels in a specific arrangement in the syringe prior to injection can allow for a single injection to achieve complex hydrogel fabrication arrangements in an *in vivo* mouse model [79••]. A more detailed review of colloidal-based scaffolds for wound healing is discussed in later sections. Overall, components with nanoscale features have shown much promise towards the creation of pro-healing materials, as they allow for excellent control over structures on similar length scales as cell-ECM interactions.

3D Bioprinting

While nanofibers and nanoparticles can be used to control nanoscale features presented to cells, traditional scaffold fabrication from these building blocks, such as electrospinning or simple particle mixing of nanoparticles with bulk hydrogels, has major limitations in patterning. 3D bioprinting, which is an additive manufacturing technology that facilitates controlled deposition of living cells, biomaterials, and factors into three-dimensional scaffolds, can be used to gain spatial control over patterning of these building blocks [80, 81]. Bioprinting is a premier scaffold construction technique which can be used to fabricate the interconnected architecture of the epidermis, dermis, and hypodermis, while simultaneously ejecting the pertinent cells of each layer into the necessary spatial arrangement [80, 82]. Kim et al. utilized minced, decellularized porcine skin tissue as a basis for their bio-ink and incorporated human neonatal dermal fibroblasts into the ink prior to printing a 3D construct. Once gelled, human keratinocytes were ejected on the top layer of the construct to form a monolayer. After a period of 7 days, the cell viability of the construct was found to be 90%, and quantities of collagen, GAGs, and hyaluronic acid were similar to that of native skin, though elastin and DNA concentrations were substantially lower. Compared with a collagen skin construct, the bio-ink construct demonstrated significantly lower contraction after 10 days in culture, greater epidermal thickness, and increased ECM secretion. For *in vivo* evaluation, the group loaded their construct with either adipose-derived stem cells (ASCs), endothelial progenitor cells (EPCs), or both simultaneously, and applied their constructs to a mouse wound model. The combined bio-ink-ASC-EPC construct demonstrated vastly improved wound closure effectiveness at 93% closure after 21 days compared with a buffer control at 70% closure. Altogether, the group demonstrated the viability of a 3D printing bio-ink to support the development of a full-thickness skin substitute [83].

There are four primary printing methods that have been used for creating pro-healing materials, including inkjet, extrusion, laser-assisted, and digital light processing (DLP) [80, 84]. Synthetic polymers, such as polycaprolactone (PCL) and poly(lactic-co-glycolic) acid (PLGA), and natural polymers, such as chitosan, collagen, and fibrin, have previously been used as bio-inks for 3D bioprinting [85, 86]; however, much room for improvement in biologically active bio-inks still remains. Some other drawbacks of 3D bioprinting are that the cell types capable of being printed in appropriate quantities are still largely in development, creating vasculature in a short time for patient-specific needs is a challenge, and current techniques lack the addition of hair follicles, sweat glands, and other features from natural skin, though this is being investigated by the addition of stem cells to scaffolds [80, 87, 88].

Cell and Tissue-Derived Scaffolds

Beyond the bottom-up-type approaches described thus far, top-down approaches to create biologic-derived scaffolds either from cell culture or whole tissue-derived scaffolds have also shown great promise for directing wound healing responses. Such materials typically take the form of ECM that is decellularized to remove immunogenic material, while leaving the physiological scaffolding structure intact. Such scaffolds can be obtained by decellularizing cell-derived ECMs or entire tissues/organs. Different tissues have different structural compositions and morphologies, and therefore, decellularized tissues from one organ may not be conducive to the growth of cells from another organ [89]. A decellularized ECM from an organ with a basement membrane and mechanical properties similar to those of the different layers of skin, or decellularized skin itself, can therefore be seeded with skin progenitor cells and used as a scaffold for wound regeneration with off-the-shelf capabilities [14, 90].

Tissue sources for decellularization can be xenogeneic, allogeneic, or even autologous, and all cellular components that can incite an immune response must be removed from the ECM scaffold prior to application [89, 91]. This is typically done through a combination of physical and chemical means, whereby a chemical such as a surfactant, hypotonic or hypertonic solution, or biological agent (enzyme) is used to disrupt membranes, lyse cells, and remove a majority of genetic material, and then a physical treatment such as freeze-drying is applied to remove the remaining material [92, 93]. Upon completion of decellularization protocols, it is important to analyze the decellularized matrix to ensure that it has not been damaged by processing, as some chemical and physical treatments have been shown to harm certain types of ECM [89]. If the matrix is found to be structurally intact, a patient's progenitor cells can be reseeded into the ECM in a bioreactor and directed to differentiate into target cells that repopulate the

matrix, manipulate the structure into the necessary skin conformation, and endow it with the patient's immune signature [94]. Some commercial decellularized pro-healing products include AlloDerm, FlexHD, and Matriderm [95].

Commercial Wound Dressings

There are numerous commercially available wound dressings and scaffolds on the market utilizing several technologies reviewed here for the treatment of wounds, including living skin substitutes, acellular naturally derived scaffolds, and biopolymeric scaffolds. Some popular living skin substitutes include Apligraf (Novartis), a bovine collagen matrix cultured with neonatal fibroblasts and keratinocytes for partial- and full-thickness wounds; Dermagraft (Organogenesis), neonatal fibroblasts cryopreserved on a polyglactin scaffold; and Theraskin (Solsys Medical), cryopreserved skin harvested from cadavers [96–98]. Some examples of acellular naturally derived scaffolds include Promogran (Acelity), freeze-dried collagen and cellulose composite material for enhancing cell migration; Integra (Integra), a collagen, glycosaminoglycan, and silicone scaffold that promotes regeneration while being biodegradable; and DermACELL (LifeNet Health), a decellularized dermal allograft to support cell ingrowth [97–99]. Finally, commonly used biopolymeric scaffolds include Talymed (Marine Polymer Technologies), shortened N-acetyl glucosamine fibers from algae for cell migration stimulation, and Hyalomatrix (Medline), hyaluronic and silicone membrane that is biodegradable [98]. Commercially available options are sure to increase in the coming years as the novel material approaches described in this review become mature technologies.

Novel Directions for Modulating the Wound Microenvironment

The technologies described thus far provide an overview of many of the methods by which the wound microenvironment may be engineered to promote enhanced healing. Within these more established fields, there are numerous novel materials and methods in development that have the potential to shape the regenerative medicine field, including the use of bioactive scaffolds, hydrogels for cell delivery, and colloidal-based materials. Recent significant advancements include microporous annealed particle hydrogels for injection and in vivo cross-linking [76••], artificial microgels which recapitulate platelet function in vivo [19, 100, 101], and injectable pH-switchable scaffolds [102••]. The following sections will detail specific examples in these areas which have been demonstrated to be of potential benefit to wound reepithelialization and tissue remodeling.

Bacterial Implications on Scaffold Design

Consideration of bacteria in wounds and the potential to harness bacteria themselves for the production of pro-healing scaffold material highlight the key role of bacteria in scaffold design for modulating wound microenvironments. Several bioactive scaffolds of various compositions are currently in development, with significant categories including those with antibacterial qualities, major structural components designed from chitosan and bacterial cellulose, and other hydrogels fabricated from a vast array of components. Some scaffolds are injectable and others have been developed to be layered directly onto the wound, some utilize controlled therapy release, and others rely on native tissue stimulation from the scaffold, but all are designed to elicit beneficial tissue repair responses once placed into the wound when compared with traditional dressing methods.

Antibacterial Scaffolds

An array of antimicrobial scaffolds has been recently devised which demonstrate wound healing capabilities while preventing the development of biofilms and infection at the wound site [102–105]. A number of materials have been employed for use as scaffolding components, which exhibit high levels of biocompatibility and incorporate metals and proteins to prevent the proliferation of various species of bacteria. Hydrogel scaffolds composed of collagen, alginate, or a combination of hyaluronic acid (HA) and corn silk extract (CSE) were loaded with gallium ions or silver particles, and cell viability and antimicrobial capability were assessed. For the collagen-gallium scaffold, a concentration of 0.025% gallium had an antibacterial potency of > 90% against *S. aureus* and *P. aeruginosa* and a slight adverse impact on cell proliferation in vitro compared with the control group, while in vivo tests in rats demonstrated a marked decrease in bacterial CFUs over a 7-day duration compared with the control [105]. For the injectable collagen and alginate gels loaded with either silver salt formulation lactate or saccharinate, in vitro results demonstrated that both collagen-silver scaffolds and alginate-silver scaffolds were effective against *S. epidermidis* and *P. aeruginosa* bacteria compared with control, though alginate-silver scaffolds were far more dose dependent. Cell viability was heightened at lower silver doses, with alginate hydrogels generally exhibiting superior performance to collagen [103]. The thermosensitive (CSE) and HA gels loaded with silver nanoparticles exhibited a strong antimicrobial effect at silver concentrations $\geq 1.7 \mu\text{g/mL}$ against *E. coli*, *S. aureus*, *B. subtilis*, and *P. Aeruginosa*, and in vitro cell viability was 100% for silver-containing hydrogels at 24 h (same as control) but dropped to 80% viability at 72 h (lower than control) [104]. These results indicate that metallic

antimicrobials may have minor adverse effects upon cell viability but overall exhibit strong protection from wound infection.

An interesting technology developed by Wang et al. involves the development of a self-assembled antimicrobial octapeptide, IKFQFHFD (Ac-Leu-Lys-Phe-Gln-Phe-His-Phe-Asp-NH₂), which can be used to produce a pH-switchable hydrogel. The hydrogel itself has been engineered to be biocompatible at neutral pH and have antimicrobial properties in acidic pH, while also having the capability of being loaded with biomaterials for wound healing applications. This hydrogel was tested against *S. aureus*, *E. coli*, *P. aeruginosa*, and *B. subtilis*, and shown to have strong antimicrobial features at low pH. Biocompatibility was also analyzed using a live/dead assay, and cell viability was determined to be 84% at pH 5.5 and 95% at pH 7.4. Used alone, the IKFQFHFD hydrogel functioned poorly to eradicate a fully formed MRSA biofilm, but when loaded with a photothermal dye and irradiated to induce heat damage, the hydrogel-dye-radiation combination was found to be sufficient for the destruction of the biofilm, with the hydrogel acting as a controlled release material with a change in pH. The group confirmed the feasibility of the hydrogel on an in vivo diabetic mouse wound model by testing the combined hydrogel loaded with the cypate dye and proline, an amino acid associated with wound healing and radiation treatment, and found that the technique significantly reduced wound healing time compared with control groups, reaching 100% closure around day 20 compared with around 45% closure for the PBS control on the same day [102••].

Naturally derived chitosan scaffolds have also been used extensively as antimicrobial scaffolds to promote healing. Chitosan is a natural scaffolding material derived from the exoskeletons of arthropods. Recent advancements have seen the utilization of chitosan as a major co-component of hydrogels for conferring antibacterial and cell proliferative qualities, and gels have been developed for loading, injection, and dressing purposes. Researchers have conjugated chitosan with pluronic 123 polymer and loaded it with curcumin or combined it with HA and a catechol-loaded terpolymer for controlled release and have cross-linked it with gelatin and combined it with lactose-cross-linked gelatin to produce a two-layered structure. In vitro experiments for each type of scaffold revealed that cell viability at 3 days was at least 90% for those including chitosan. In vivo experimentation was carried out in mice, rats, and ex vivo human skin explants, and resulted in some scaffolds performing better than the control groups, such as the curcumin-loaded gel [106] and catechol-loaded terpolymer [107], while the gelatin-cross-linked [108] scaffold performed more poorly than the controls. These results indicate that while chitosan-mixed scaffolds may function well in an in vitro environment, further experimentation must be conducted on their use in in vivo situations.

Bacterial Cellulose Scaffolds

While the quest for antibacterial molecules and scaffolding materials continues, novel applications for leveraging bacterial products for scaffolding have also arisen, the most predominant of which is bacterial cellulose. Bacterial cellulose is a naturally derived material used as a combination material in scaffolding due to its biodegradability, biocompatibility, and high mechanical strength. It has recently been combined with copolymer P(3HB/4HB), a polyhydroxyalkanoate (PHA) derived from microbes and having similar qualities to bacterial cellulose itself, to develop scaffolds for managing burns [109]. It was also recently conjugated with resveratrol, a non-cytotoxic naturally derived chemical that was thought to reduce inflammation and stimulate angiogenesis [110]. Both studies demonstrated favorable results with the use of bacterial cellulose as a scaffolding material, but according to in vivo experimental results in mouse models, the resveratrol-loaded bacterial cellulose scaffold may have inhibited wound reepithelialization compared with the scaffold alone by day 14, with 10% of the wound remaining without resveratrol and 20% remaining with resveratrol. P(3HB/4HB) combined with bacterial cellulose exhibited vastly improved wound healing by day 14 and when combined with fibroblasts, the wound was nearly completely sealed by this time. These results demonstrate that bacterial cellulose is a viable natural scaffolding material for wound healing that can exhibit loading potential for advanced therapeutics [109, 110].

Cell Delivery Scaffolds

Many of the scaffolds discussed thus far can be used alone or in combination with cell or cell-derived factor delivery to enhance healing outcomes. Common strategies include delivering fibroblasts, keratinocytes, stem cells, and platelet-rich plasma (PRP) via scaffolds directly to the wound site. As previously discussed, fibroblasts and keratinocytes are primary cell types of the skin layers that produce ECM and form the protective physical outer layer of the skin and are therefore important for delivery. Stem cells are also critical to wound healing applications and can be found in all three layers of the skin, though they are primarily located in the epidermis [4•]. Platelet-rich plasma is another cell-rich product that can be delivered in scaffolds to exhibit wound healing potential. PRP is obtained from centrifugation of autologous patient blood and contains a high concentration of platelets and growth factors beneficial to wound reepithelialization [111]. PRP regulates inflammation, stimulates angiogenesis, aids in the remodeling of tissue, is cost-effective, and non-immunogenic for autologous use [111–113]. PRP can be delivered topically or in scaffolds and dressings [111].

Many types of stem cells have been investigated for use in pro-healing scaffolds. Adult stem cells, which can be derived from hair follicle, epidermis, and mesenchymal stem cells (MSCs), are popular selections and have been shown to secrete various growth factors and cytokines that aid in the wound repair process [114, 115]. These stem cell sources can differentiate into keratinocytes [116]. When delivered into the proper environment that has correct mechanical characteristics, temperature, pH, and oxygen concentration that recapitulate the skin microenvironment, stem cells can be induced to differentiate into target skin cells [4•]. However, the delivery of stem cells without a carrier material has been shown to result in low retention of cells at the wound site and a high loss of viability. Therefore, much effort has recently been dedicated to optimizing scaffold design for stem cell delivery/retention at the wound site via methods such as encapsulation and topical application. For example, a scaffold for encapsulation and delivery of MSCs in a thermosensitive chitosan/glycerol phosphate sodium/cellulose nanocrystal hydrogel was recently devised by Xu et al. This material combination enabled the formation of a viable, injectable, self-healing, and self-assembling scaffold in vivo while encapsulating MSCs for direct delivery into the wound site. The scaffold demonstrated similar cell viability and wound closure rates to the control group, reduction of inflammation, and promotion of angiogenesis [117].

Another injectable scaffold, developed by García et al., activated the immunomodulatory functions of encapsulated MSCs by tethering interferon-gamma (IFN- γ), a pro-inflammatory stimulus, to a PEG hydrogel. The IFN- γ has been found to cause MSCs to secrete immunoreactive factors including indoleamine, programmed death ligand-1 (PD-L1), and prostaglandin E2 (PGE2) in a process called licensing. Encapsulated MSCs were found to secrete significantly increased concentrations of immunoreactive factors in scaffolds with IFN- γ compared with scaffolds without after 4 days in culture, and in vivo studies in immunodeficient and immunocompetent mouse intestinal mucosal wounds 5 days after treatment with the hydrogel demonstrated significant wound closure rate increases over controls such as hydrogels with MSCs but without IFN- γ , hydrogels alone, MSCs alone, and no treatment. Also, wounds examined after 4 weeks showed the continued presence of MSCs at the wound site [118•]. While these studies were performed using intestinal mucosal wounds, similar approaches could be useful for modulating the healing environment in skin wounds.

Scaffolds for stem cell delivery which are topically applied have also been described. Huang et al. produced a 3D-bioprinted PCL and bacterial cellulose scaffold seeded with MSCs, thereby creating a skin substitute. The mechanical properties were found to be similar to those of native human skin, cells seeded onto the scaffold showed a 99% viability after 3 days, cells demonstrated a paracrine effect in vitro for

factor release, and in vivo results indicated a much greater wound closure rate in 10 days using the artificial skin (95%) compared with PBC scaffold (75%) and no wound coverage (58%) [119]. Together, these scaffolds represent multiple means of delivering MSCs into a wound and demonstrate the influence these cells have on wound healing kinetics compared with acellular scaffolds of the same materials.

Colloidal-Based Wound Healing Materials

A number of colloidal-based materials have been produced which modify the wound microenvironment, either via delivery of bactericidal and growth factors using nanoparticle approaches or by using the nanoparticles themselves as a direct method of bolstering the natural wound healing process. These treatments can be applied directly to the skin or injected into the wound site with minimal toxicity to the patient.

As previously discussed, growth factors and bactericidal chemicals are valuable components for drug delivery to wound sites, which may have a significant impact on wound closure rates, cell viability, and cell proliferation. Some labs have developed nanoparticles for delivery of these components, including bactericidal terbium oxide (Tb₄O₇) nanoparticles and antimicrobial and growth factor-delivering PLGA nanoparticles [120, 121]. The Tb₄O₇ NPs were found to have intrinsic oxidase-like activity at acidic pH levels and behave as enzymes (nanozymes), while the PLGA NPs encapsulated VEGF, basic fibroblast growth factor (bFGF), and antimicrobial peptide (AMP) K4, and were designed to protect their cargo from enzymatic degradation. The Tb₄O₇ NPs reduced the survival of *S. aureus* and *E. coli* to 10% at a concentration of 100 μ g/mL and 50 μ g/mL respectively, while PLGA-K4 NPs reduced survival of *S. aureus* and Gram-negative *P. aeruginosa* to 40% and 30% respectively. In vitro viability of HUVECs was shown to be > 80% for all concentrations of Tb₄O₇ NPs used, with < 20% of wound area and < 5% of bacterial concentration remaining after day 5 compared with PBS treatment in mice, while PLGA-K4 NPs showed improved in vivo cell viability and 24-h scratch wound migration rates over PLGA-NP control, though the antibacterial K4 appeared to counteract the effects of the growth factor slightly.

Another popular colloidal material for wound healing is bioactive glass, which exhibits antibacterial and angiogenic properties. Some labs have complexed silver and gold with bioactive glass to produce micro- and nanoparticles for both injection and topical application for therapeutic purposes. In one case, silver was incorporated directly into glass nanoparticles, and these particles were shown to cause a nearly five-orders-of-magnitude decrease in CFU concentration of *S. aureus* compared with no treatment, while no effect was shown against *P. aeruginosa* in a 3D tissue-engineered infected skin model. Cell metabolic rate was shown to be the same

between the experimental group and the control group, indicating that there was no *in vitro* cytotoxicity [122]. In another case, Mârza et al. produced an ointment by encapsulating gold nanoparticles in glass and milling into a powder, which was then added to Vaseline. The resultant ointment was then tested for cell viability of keratinocytes *in vitro* and demonstrated over 100% viability after 24 h, indicating that cell proliferation occurred. For *in vivo* studies, the ointment was topically applied on days 0, 3, and 7, and BG-Vaseline and BG-AUNP-Vaseline groups performed equally as well in mouse wound closure testing and exhibited more rapid wound closure rates early in the treatment process than the control of no treatment [123]. These uses of bioactive glass as colloids for enhanced wound regeneration demonstrate its promise as an effective synthetic wound microenvironment modulator.

Other colloidal-based wound therapies focus on the injection of colloids directly at the wound site to form a scaffold, which incites the body's cells to modify the scaffold structure. One approach takes advantage of several of the technologies previously described, including *in vivo* microgel self-assembly and the use of MSCs, which were co-injected with the scaffold. Koh et al. developed mechanically tunable PEG-based microporous annealed particle (MAP) microgels which could be injected and enzymatically cross-linked *in vivo*, creating pores between particles capable of entrapping and protecting MSCs that were co-injected with the microgels, as well as oxygen and nutrients necessary for cell proliferation (Fig. 3). After performing the injection in mice and comparing it with a nonporous scaffold and PBS-only treatments, MAP/MSC scaffolds demonstrated enhanced cell retention, migration, and proliferation at the scaffold site, proving this co-injection system to be a useful cell delivery and scaffolding method [124]. Leveraging MAP technology, Isaac et al. produced a PEG MAP hydrogel via electrospinning which can be annealed *in situ* using bio-orthogonal tetrazine click chemistry (TzMAP hydrogel). A tetrazine-norbornene reaction can be activated by injecting PEG-norbornene microgels and PEG-di-tetrazene cross-linker into the wound site and allowing a 3D scaffold to form. The group found that this material could act as a controlled release material for PDGF-BB, and cell viability data collected 24 h after encapsulating periodontal ligament stem cells into the hydrogels during the microporous annealing step *in vitro* was determined to be 87% [125]. These experiments demonstrate the potential of MAP technology for the advancement of colloidal-based wound healing approaches. Another synthetic colloidal approach involves the construction of ultralow cross-linked (ULC) poly(N-isopropyl-acrylamide) (pNIPAm) microgels to create synthetic platelet-like particles (PLPs) for simulating platelet interactions in the wound environment. As previously described, platelets are a critical component of the wound healing cascade and aid in hemostasis and clot retraction. Nandi et al. detailed the process of developing these PLPs and found that

the ULC base particle is capable of deforming like an activated platelet, ULCs conjugated to fibrin-targeting antibodies to form PLPs are capable of generating contractile forces and enhancing fibroblast migration *in vitro*, and PLPs demonstrate enhanced wound closure rates *in vivo* over saline controls [101]. Additional studies have corroborated these results, as well as exhibited the antimicrobial activity of these PLPs when complexed with colloidal gold [19, 100]. Another similar colloidal technology produced by Muhamed et al. is injectable fibrin-based nanoparticles (FBNs) which have similar porosity and composition to the native clot structure and are designed to be integrated into clot assembly. *In vitro* analysis showed that FBNs support fibrin scaffold formation and increase scaffold formation rates, while *in vivo* analysis in mice indicated that growth factors could be covalently bound to FBNs to increase wound closure rates over controls [126]. Colloidal-based wound healing therapies are an innovative and evolving component of microenvironment moderation, offering an alternative approach to traditional scaffold development therapies. Colloids allow for flexibility in material choices, high tunability of the underlying material mechanical properties, and delivery of therapeutic molecules to the wound site. They have the ability to combine many of the properties overviewed in previous sections of this review, increasing therapeutic potential.

Conclusions and Future Outlook

Biomaterials are critical tools for overcoming chronic non-healing wounds, which account for a significant portion of annual medical costs and patient morbidity. This review has highlighted several strategies currently under investigation for combating wounds and moderating the wound microenvironment, including wound dressings, hydrogels, nanomaterials, and scaffolds produced via electrospinning, 3D printing, and acellular materials. Emerging strategies for modulating the wound environment, including novel methods for enhancing the delivery of MSCs into the wound, various antimicrobial and growth factor biomolecules for addition to dressings and scaffolds, and novel colloidal scaffold-based approaches were discussed.

Despite the vast array of materials developed for this issue, there are still areas requiring further investigation. Materials have managed to replicate the basic characteristics of the skin, but the incorporation of advanced features such as hair, hair follicles and their stem cells, and sweat glands into artificial dermal scaffolds has yet to be successfully achieved. Scaffolding materials such as chitosan also require further investigation, as their *in vivo* viability may require further testing and analysis. Novel technologies such as injectable self-assembling scaffolds, granular jamming microparticle hydrogels, and MAP hydrogels offer a promising outlook

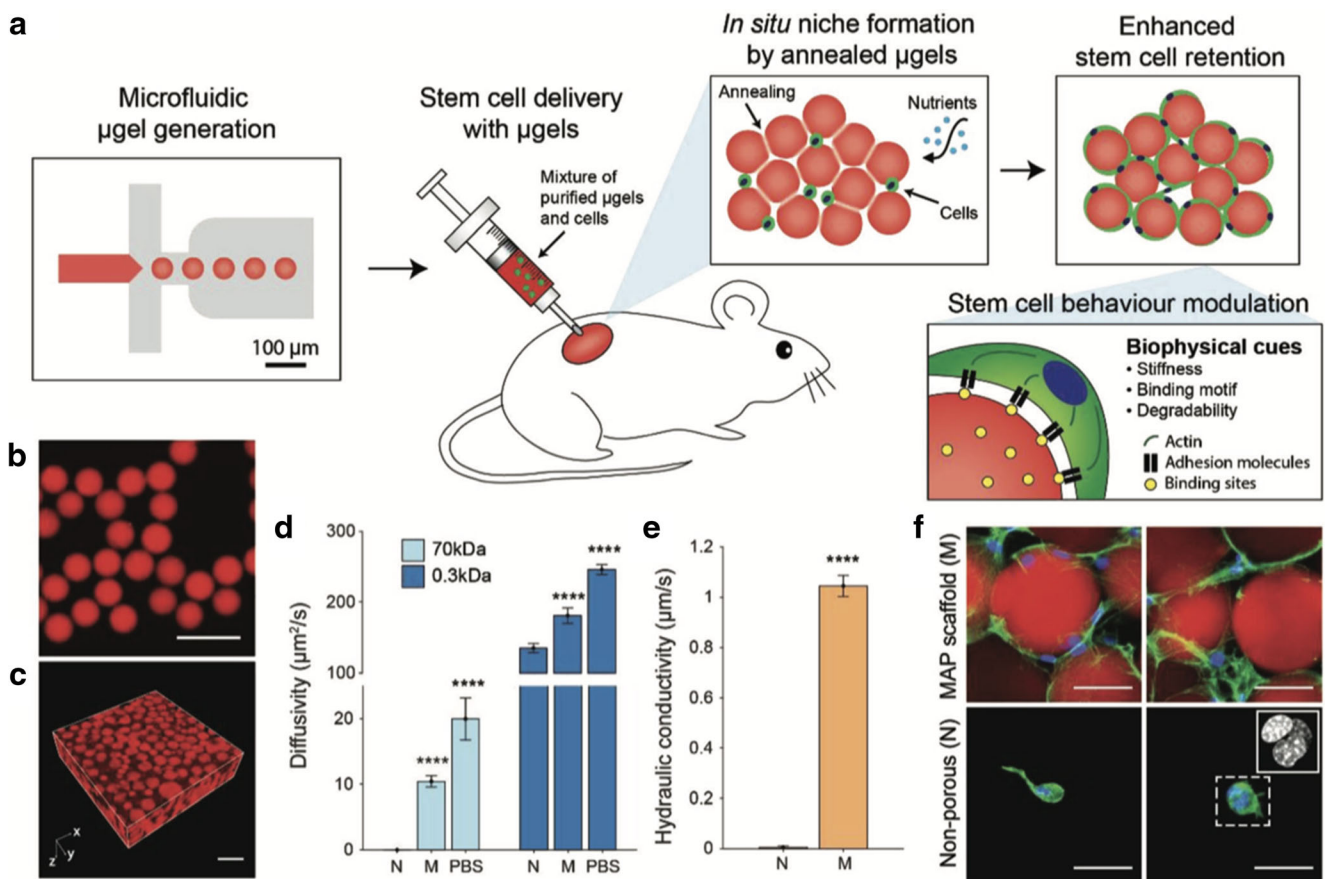


Fig. 3 Mesenchymal stem cell (MSC) delivery and *in situ* niche creation strategy using annealed monodisperse hydrogel particles. **a** An artificial stem cell niche is created *in situ* by annealing a suspension of injectable monodisperse hydrogel particles. Highly monodisperse particle building blocks enable the generation of a pore network in a highly controllable manner, which promotes the transport of oxygen and nutrients as well as cell migration. The biophysical properties of building blocks are modulated to enhance the functions of the transplanted MSCs. **b** Monodisperse hydrogel particles or microgels produced by the microfluidic device. Scale bar 200 μm. **c** Tissue scaffold assembled from monodisperse microgels. Scale bar 200 μm. **d** Diffusivity of

70 kDa dextran and 0.3 kDa FITC in nonporous scaffolds (N), MAP scaffolds (M), and PBS ($n = 4-7$). Data are presented as average \pm SD. Statistical significance based on one-way ANOVA followed by Tukey’s HSD post hoc test (significance compared with N, **** $p < 0.0001$). **e** Hydraulic conductivity of PBS through the nonporous scaffold (N) and MAP scaffold (M) at atmospheric pressure ($n = 3$). Data are presented as average \pm SD. Statistical significance based on standard two-tailed Student *t* test (**** $p < 0.0001$). **f** Fluorescent images of MSCs *in vitro* cultured in microporous scaffolds and nonporous scaffolds at week 2. Blue, nucleus; green, actin; red, gel. Scale bar 50 μm. Reproduced from Koh et al. [124]

for the advancement of the field. Additionally, combinations of existing and emerging technologies, such as bioprinting of microparticle hydrogels and the inclusion of drug-eluting nanoparticles into bulk hydrogels and/or electrospun fibers to create composite materials, offer a myriad of options for expanding the possibilities of wound microenvironment modification. Overall, biomaterials strategies for modulating the wound microenvironment have the potential to extensively improve treatment outcomes for patients with chronic non-healing wounds.

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Compliance with Ethical Standards

Conflict of Interest Dr. Brown reports grants from the American Heart Association, National Science Foundation, and North Carolina State University Chancellor’s Innovation Fund, during the conduct of the study. In addition, Dr. Brown has a patent issued for functionalized microgels with fibrin-binding elements, a patent pending for 3D printing of colloidal building blocks for wound healing materials, a patent pending for fibrin nanoparticles that enhance wound healing, and a patent pending for microgel-nanoparticle composites for fighting infection and promoting wound repair. Mr. Scull has nothing to disclose.

Human Studies/Informed Consent All reported studies/experiments with human or animal subjects performed by the authors were performed in accordance with all applicable ethical standards including the Helsinki declaration and its amendments, institutional/national research committee standards, and international/national/institutional guidelines.

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