Peer-reviewed version available at *Polymers* **2018**, *10*, 1078; doi:10.3390/polym10101078

Review

Incorporation of Conductive Materials into Hydrogels for Tissue Engineering Applications

Ji Hong Min [1, 2] and Won-Gun Koh [1,*]

[1] Department of Chemical and Biomolecular Engineering, Yonsei University, Seoul, Republic of Korea
[2] Active Polymer Center for Pattern Integration (APCPI), Yonsei-ro 50, Seoul, Republic of Korea
*** Correspondence:** wongun@yonsei.ac.kr; Tel.: +82-2-2123-5755

Abstract: In the field of tissue engineering, conductive hydrogels have been the most effective biomaterials to mimic the biological and electrical properties of tissues in the human body. The main advantages of conductive hydrogel include not only its physical properties, but also its adequate electrical properties, thus providing electrical signals to cells efficiently. However, when introducing a conductive material into a non-conductive hydrogel, a conflicting relationship between the electrical and mechanical properties may develop. This review examines the strengths and weaknesses of the generation of conductive hydrogels using various conductive materials and introduces the use of these conductive hydrogels in tissue engineering applications.

Keywords: conductive hydrogel; tissue engineering; biomaterials; physical and electrical properties

1. Introduction

A hydrogel, which can stimulate the function of native tissues, has been an increasingly essential issue in the field of tissue engineering resulting from aging, injuries, or diseases [1, 2]. It can provide a 3D hydrated polymeric network that, can be synthesized in various shapes and sizes because of its unique physical properties. Mimicking a complex tissue structure and providing an essential cellular microenvironment are essential elements that need to be considered to manage the formation of functional tissue in a fabricated hydrogel.

Among the various biomaterials, a conductive hydrogel is one of the most effective materials to replicate the electrical and biological characteristics of biological tissues that require most of the conductivity [2-4]. The advantage of a conductive hydrogel is that it can provide both physical and electrical properties, where the former is the unique property of the hydrogel and the latter is the conductivity performed by the conductive materials [2, 5]. There have been many studies of designed biomaterials with controlled electrical properties would be useful in promoting the formation of functional tissues [6, 7]. To provide a cell-effective conductive environment, conductive hydrogels have been synthesized via various techniques and with conductive materials that, either obtain biocompatibility or effectively provide an electrical cue to cells for restoring the functions of cellular tissues and satisfy the high needs of biomedical applications.

In this review, we first focus on detailed introductions of the types of conductive hydrogels; in particular, the emerging trends in conductive materials such as metal nanoparticles, conductive polymers, and carbons. Details are provided on the methods for synthesizing conductive hydrogels based on a blending process, in situ process, and coating process. We also address biomedical applications in the heart, cardiac, and neuronal fields, which have been actively studied in the field of tissue engineering using conductive hydrogels. Then, we discuss the future perspective of conductive hydrogels in the field of tissue engineering.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

2. Types of Conductive Hydrogels

The conductive hydrogel can implement a variety of fabrication systems depending on the type of materials or fabrication methods. The former is classified as material and the latter as a production method.

2.1. Materials

2.1.1. Metal Nanoparticles

Metal nanoparticles are nanometer-sized ultrafine particles and behave differently depending on the type, shape, and size of the material (Figure 1) [8, 9]. Researchers have confirmed that the characteristics of metal nanoparticles can be changed depending on the size of the nanoparticles. The overall results of a mathematical model showed that the conductivity of a metal nanoparticle can be decreased when the particle size is smaller, confirming the experimental results of [10]. By functionalizing nanoparticle surfaces, the interaction between a polymer and nanoparticles can be strengthened [11-13]. Various types of metal nanoparticles have been used in the production of nanocomposite hydrogels in the field of biomaterials including gold [14], silver [15] and other noble metal nanoparticles, while metal oxide nanoparticles such as iron oxide [16] and zirconia [17] have also been used. Since metal and metal oxide nanoparticles possess the desired electrical conductivity, magnetic properties, and antibacterial properties, nanocomposite hydrogels that contain metal or metal oxide nanoparticles are widely used in conductive scaffolds, electronic switches, actuators, and sensors [18-21].

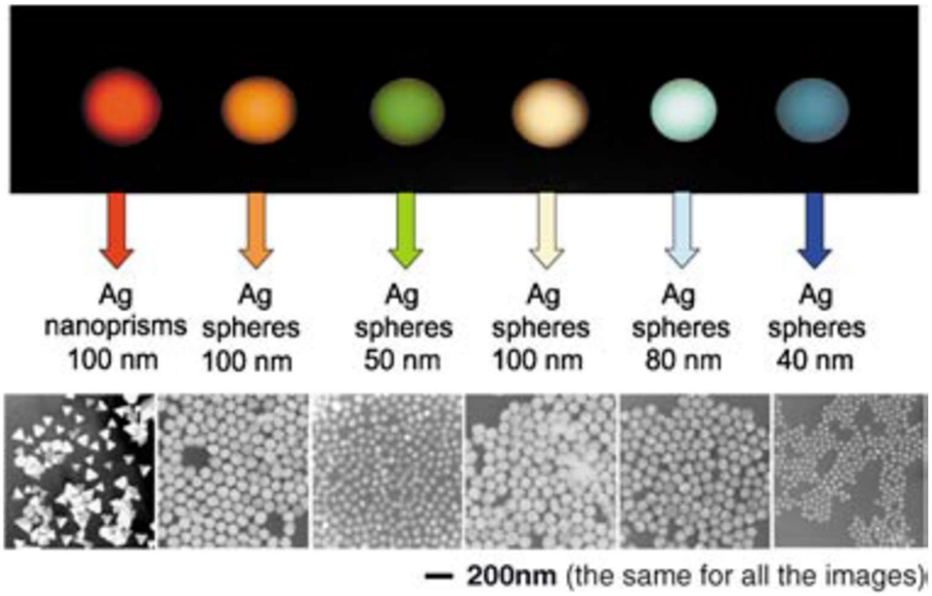


Figure 1. Nanoparticles behave differently depending on the size and shape of the material. This figure shows the difference of the Rayleigh light-scattering properties of silver nanoparticles. (reproduced with permission from **[8]).**

Table 1. Properties of Metal Nanoparticles

Kinds of Nanoparticles	Size (nm)	Shape	Advantages	Disadvantages	Application
Gold Nanoparticles (AuNPs)	1-60	Spherical Rod Polygonal Floral	- High stability - Low cytotoxicity in initial step - Possibility of high scale production	- Relatively weak optical signal - Long-term cytotoxicity - High price	Labelling and visualization, Diagnostic, Therapeutics, Catalysis, Cancer cell treatment
Silver Nanoparticles (AgNPs)	4-120	Spherical Wire Oval Polygonal Rod	- Anti-microbacterial - High optical signal	- Cytotoxicity - Low stability before surface treatment - High price	Anti-microbial, Gas/ Vapor sensing, Water sterilization, Cancer cell treatment
Platinum Nanoparticles (PtNPs)	10-100	Spherical Cuboidal Floral	- Catalysis - High optical signal - High stability	- High price - Cytotoxicity	Biosensing of molecules, Enhancing bone strength, Detection of cancer cells
Iron Oxide Nanoparticles	4-45	Tube Spherical Cluster	- Super-paramagnetic property - Low cytotoxicity - Economical	- Weak strength - Low stability - Toxic solvent is needed	Gas sensing, Magnetic resonance imaging
Zinc Oxide Nanoparticles	20-600	Flower Rod Wire Sheet	- Piezo- and pyroelectric - Wide range of UV absorption - High optical signal - Economical - Anti-bacterial effect	- Cytotoxicity - Low stability - Toxic solvent is needed	Photocatalyst, Absorber of UV radiation, Biosensors, Gas sensing

Gold nanoparticles (AuNPs) are one of the most essential metal nanoparticles actively used in biomedical fields. Methods for synthesizing AuNPs generally include nanoscale lithography,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

chemical, electrochemical, photochemical, and thermal reduction techniques [22] and, have led to the creation of various shapes and sizes of AuNPs. They have been utilized in various visualization and bioimaging techniques [23], photothermal therapy for targeting the injury of tumor tissue sites [24-27], antigen detection, and immunostaining research used in radioactive labeling [28]. In addition, gold metals can provide electrical conductivity. Conductive hydrogels can be developed so that they can provide both hydrogels and additional attributes of AuNPs. Although AuNPs are weak optical signals and have a long-term cytotoxicity, they have been an attractive option in terms of providing both conductivity and unique properties. Baei et al. synthesized a thermosensitive conductive hydrogel by combining AuNPs with chitosan (Figure 2) [29]. The gelation and conductivity of the hydrogel were controlled by the concentration of the AuNPs and supported the metabolism, viability, migration, and proliferation of myocardial cells.

Silver nanoparticles (AgNPs) have also been commonly used in biomedical applications because of their inherent characteristics of unique optical, electronic, and antibacterial properties. Synthesizing techniques for AgNPs include, laser cutting, gamma irradiation, electron irradiation, chemical reduction, photochemical methods, microwave treatment, and biological synthesis methods [30]. Based on these techniques, the adjustment of size and agglomeration of AgNPs can control antimicrobial activity [31-35]. Free electron vibrations in silver nanostructures cause radioactive decay because of the strong visible light scattering of light or non-photon destruction [36, 37], which can be used to image or treat diagnoses [38, 39]. AgNPs are promising materials that can be utilized in the production of conductive hydrogels as materials and provide unique factors including strong antibacterial effects, optical properties, and conductivity. The possibility of the cell death because of excessive antibacterial effect or the reduced uniformity of conductive hydrogels because of excessive agglomeration by decreased nanoparticle stability is a challenge in the production of a conductive hydrogel. Nevertheless, it is expected that AgNPs can be used in conductive hydrogels to control conductivity and optical / antibacterial properties.

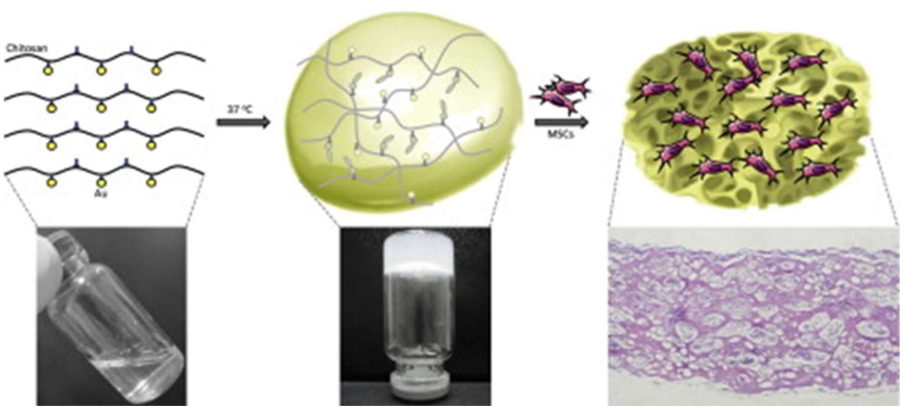


Figure 2. Thermosensitive conducive hydrogel by combining AuNPs with chitosan. The potential of AuNPs as a material of conductive hydrogel was confirmed (reproduced with permission from [29]).

Platinum nanoparticles (PtNPs) are promising versatile metal nanoparticles that have been applied in various research applications in recent years. Various synthesis methods have been devised for PtNPs, including chemical reduction using chemical solutions and physical synthesis using electron beam evaporation [40]. PtNPs have been used as catalysts, biosensors, and in many other biomedical applications because of their unique catalytic and optical properties. In particular, detection using PtNPs showed excellent catalytic properties and has been used for the electrochemical analysis of living bodies [41, 42]. In addition, research results have reported that PtNPs can be used as biocatalysts through various shapes of PtNPs, such as nanotubes and nanofibers [43]. Despite successful results, PtNPs have limited applicability in the field of biomedical research. However, conductive hydrogels with PtNPs have been expected and studied as a bioreactor because of the catalytic property of PtNPs.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at *Polymers* **2018**, *10*, 1078; doi:10.3390/polym10101078

Metal oxide is a metallic compound formed by combining metal and oxygen with a forming oxide ion. In general, metal oxides are known to exhibit interesting nanomorphisms or functional biocompatibility, non-toxicity, and catalysis. These materials have high electron transfer kinetics or strong adsorption ability that can provide an environment suitable for the immobilization of biomolecules and can impart improved electron transfer and biosensing characteristics. Iron oxide nanoparticles have been used in many in vivo applications including the enhancement of magnetic resonance imaging contrast and treatment, tissue repair, immunoassay, fluid decontamination, and cell sorting [44,45]. . fluid decontamination, and cell sorting. Zinc oxide nanoparticles are metal oxides with a wide range of applications and possess unique optical, chemical sensing, antibacterial [46, 47], electrical conductivity, and piezoelectric properties [48]. In addition, research results have shown that TiO2 [49] and ZrO2 [50] nanoparticles enhance the strength and conductivity of supported substrates. Nonetheless, metal oxides have low stability compared to other materials. Therefore, to compensate for such a disadvantage, experiments have been conducted to modify surfaces or to mix these materials with other substances to compensate for these drawbacks [51, 52].

2.1.2. Conductive Polymers

Conductive polymer (CP) is an organic an electronically conjugated polymer material loosely fixed on a backbone with electro-optic properties similar to those of metals [53]. Since pi-electrons move freely, they can form electrical pathways of mobility charge carriers [54, 55]. The usage of conducting polymers allows a hydrogel to provide electrical stimulation locally and enhance the physical properties of the hydrogel as a template to accurately control the extent and duration of external stimulation [56-58]. Conductive materials like, polypyrrole (PPy), polyaniline (PANi), polythiophene (PT), and poly (3, 4-ethylene dioxythiophene) (PEDOT), have been widely used in conductive hydrogels (Figure 3).

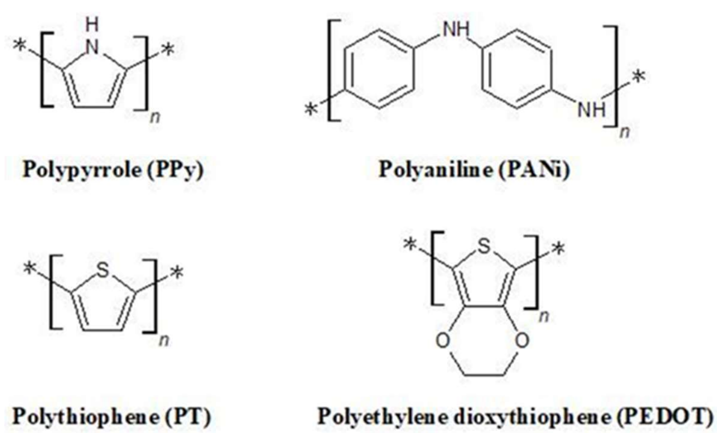


Figure 3. . Chemical structures of various conductive polymers.

Table 2. Bulk Properties of Conductive Polymers

Kinds of Conductive Polymers	Conductivity (mS · cm^{-1})	Advantages	Disadvantages	Application
Polypyrrole (PPy)	10^3 ~ 5×10^4	- High conductivity - High stability - Biocompatibility - High mechanical strength	- Easy to Fragile - Susceptible to irreversible oxidation - Insoluble in water	Biosensors, antioxidants, drug delivery, neural prosthetics, tissue engineering
Polyaniline (PANi)	10^2 ~ 10^8	- High conductivity - High stability - High conductivity - Water solubility	- Lack of plasticity - Controversy in cell adhesion and growth - Low solubility	Biosensors, antioxidants, drug delivery, bioactuators, food industry, tissue engineering
Polythiophene (PT)	10^{-1} ~ 10^{-4}	- Good optical property - Biocompatibility - Can obtain various functions according to the reactions	- Low conductivity - Low stability - Low solubility	Biosensors, food industry, tissue engineering
poly (3,4-ethylene dioxythiophene) (PEDOT)	3×10^5 ~ 5×10^5	- High stability - High conductivity - Biocompatibility - High mechanical strength - Water solubility (doped with PSS)	- Relatively low mechanical strength	Antioxidants, drug delivery, neural prosthetics electrode

As the most studied conductive polymer, PPy has been synthesized by chemical oxidation using a radical initiator with an appropriate electrolyte solution [59, 60] or by electrochemical oxidation of pyrrole with an electrolyte solution on a platinum-coated electrode [61]. PPy has been reported to offer focal adhesion and the growth of various cell types associated with endothelial cells [62, 63], neurons, supporting cells (DRG) [64-66], and rat pheochromocytoma (PC12) cells [66-69]. Yang et al. devised conductive hydrogels of hyaluronic acid and PPy that enhanced mechanical and conductive properties [70] (Figure 4). In this study, PPy/hyaluronic acid hydrogels were 5-fold of Young's modulus compared to uncoated hyaluronic acid hydrogels and had 7.3 mS · cm^{-1} of conductivity. However, the unreformed and straightforward form of PPy can be synthesized to have an additional small biological anion (Cl-) as a dopant to confer additional biological properties or to improve the stability of PPy. It can be innovated to support growth of various cell types and to encourage specific aspects of wound healing by simply changing the dopant [71-73]. Furthermore, it

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

is essential to consider controlling the mechanical properties. Since unchanged PPy, like most other CPs, is crystalline, fragile, and susceptible to irreversible oxidation [74], there is no ideal candidate for tissue support materials. Therefore, to overcome such disadvantages, the development of dopants and PPy analogs are continuously being researched [75].

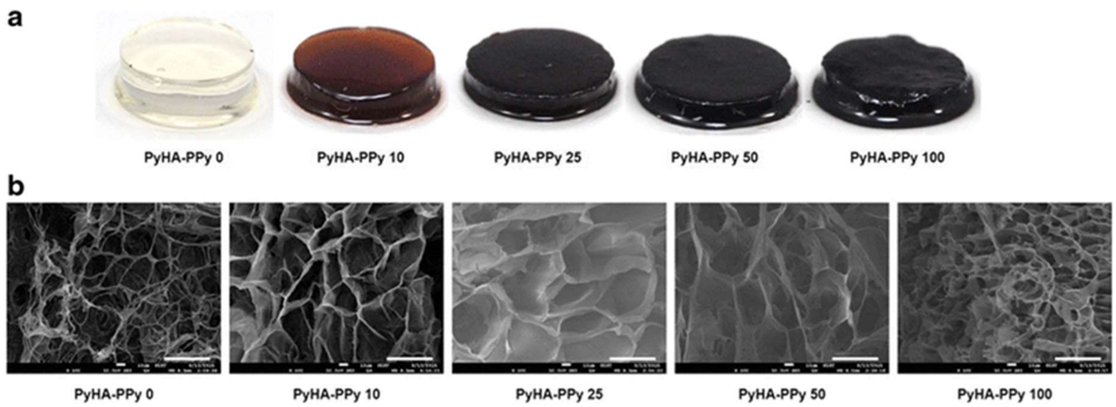
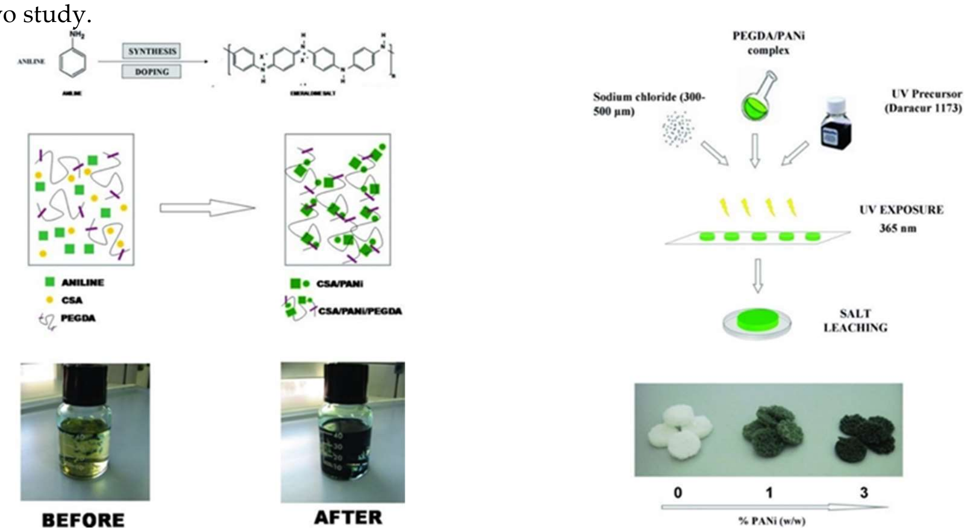


Figure 4. PPy/hyaluronic acid hydrogels; (a) various PyHA-PPy hydrogels, and (b) SEM images of PyHA-PPy hydrogels (reproduced with permission from [70]).

Another frequently used CP is PANi, which is a substance polymerized chemically or electrochemically with monomeric aniline. Several strategies have been proposed on the development of PANi with excellent cardiac and PC12 cells cell compatibility [76], conductivity, and mechanical properties. As a result of studying the in vivo response of PANi in various oxidation state implants, it was confirmed that severe inflammation did not occur in the implant site in general [77]. However, several studies have investigated the undeformed biocompatibility of PANi, and there has been controversy over unregulated PANi in that it is incomplete in cell adhesion and growth [78]. For these reasons, various methods have attempted to physically fabricate hydrogel with the desired electrical properties of the material and PANi [79, 80]. For example, PANi-PEG conductive hydrogel was prepared by the precipitation of PANi in a polyethylene glycol diacrylate (PEGDA) solution, then, a crosslinking of UV irradiation occurred (Figure 5) [81]. The hybrid material improved conductivity with its hydrophilic nature and showed that an optimization of 3wt% PANi improved the biological reaction of PC12 and human mesenchymal stem cells (hMSCs) in vivo study.



(a) (b)

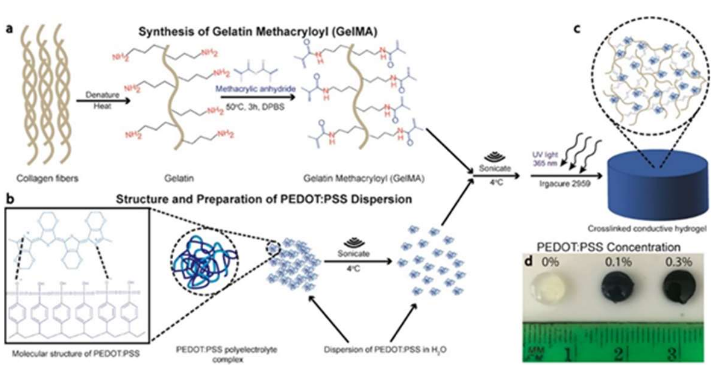
Figure 5. (a) In situ CSA-PANi synthesis in PEGDA solution and (b) preparation of PANi/PEGDA microporous hydrogels (reproduced with permission from [79]).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

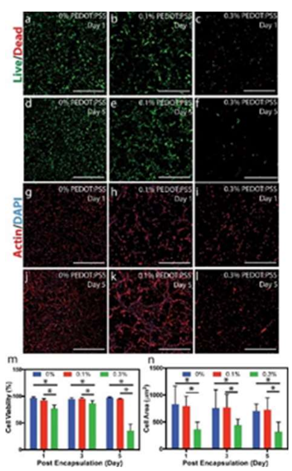
Peer-reviewed version available at *Polymers* **2018**, *10*, 1078; doi:10.3390/polym10101078

For the purpose of tissue engineering, various CPs including PT and new CP were sought in addition to the most studied PPy and PANi for conductive hydrogels. PT is synthesized with various cross-coupling reactions using transition metal, nickel and palladium catalysts, oxidative polymerization, electrochemical polymerization and biocatalyzed polymerization. PTs can easily acquire various functions by the organic reaction of substituted thiophene monomers and new properties can be obtained through the polymerization of these functionalized monomers [82]. Although the shortcomings of conductive stability and mechanical integrity have been a problem for long-term performance deficiencies, the functionalized PT of the optimized structure can be used to alleviate the problems of existing materials.

PEDOT is utilized in various studies because it has biocompatibility characteristics similar to those of polythiophene derivatives and melanin, which is a natural biological substance [83-85]. Another advantage of PEDOT is that the monomer is hydrophilic, thus, enabling them to be soluble in water and easy to tailor its composition by blending with different materials in the synthetic aqueous system of other polymers [86, 87]. In general, PEDOT has been doped into poly styrene sulfonate (PSS) to obtain an excellent film-forming ability and hydrophilic polyelectrolyte system [88]. Spencer et al. prepared composite conductive hydrogels from PEDOT: PSS dispersed within photo-crosslinkable gelatin methacryloyl (GelMA) hydrogels (Figure 6) [89]. The doped PEDOT-PSS adjusts the band gap to improve conductivity and provide excellent stability in the doping state [90]. In addition, the advantages of PEDOT: PSS film is its compatibility and stability with most organic solvents during the manufacturing process [91].



(**a**)



(**b**)

Figure 6. Study of GelMA / PEDOT : PSS hydrogels (a) scheme of GelMA/PEDOT:PSS hydrogel synthesis and (b) representative LIVE/DEAD images and quantification of cell spreading from C1C12 cells encapsulated in different amounts of PEDOT:PSS (reproduced with permission from [89]).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

2.1.3. Carbons

Graphene and carbon nanotubes (CNTs) applied as a conductive material of a biomatrix can enhance cell attachment and proliferation. Graphene is a single layer mineral graphite that has variety of physical and chemical properties, which include superconduction, high surface area, excellent thermal conductivity, and muscular mechanical strength [92-94].

Graphene can be mass-produced by thermally decomposing SiC wafers under graphene oxide (GO) chemistry, mechanical exfoliation, chemical vapor deposition, and liquid-phase exfoliation (Figure 7) [93]. In the laboratory, although the yield is low, highly pyrolyzed graphite is repeatedly peeled off graphite to produce a graphene sheet [95]. Mechanical strength is one of the several advantages of using graphene and can be changed by adjusting the graphene concentration. Therefore, the preparation of hydrogel containing graphene has been applied to various fields including energy storage [96], catalysts [97], and sensors [98]. Lee et al. showed that graphene film improved MSC proliferation and differentiation when compared to a polydimethylsiloxane (PDMS) film. The graphene film acts as a reserve platform for bone formation inducers and advances the growth of MSCs in the osteogenic lineage because of their strong non-covalent binding [99]. However, adjacent graphene sheets can interfere with applications [100] because of the serious aggregation owing to pi-pi interactions and cytotoxicity. Nevertheless, they are expected to be used in the production of conductive hydrogels through graphene surface modification, mixing with other materials, and hydrogel encapsulation to provide excellent conductivity.

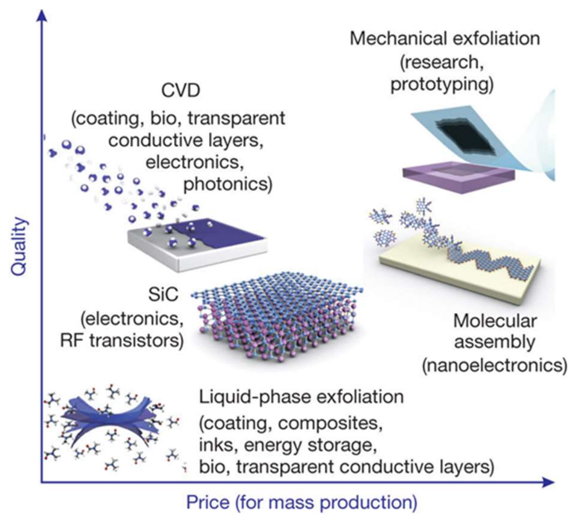


Figure 7. Several methods of mass production of graphene in terms of size, quality and price (reproduced with permission from [93]).

GO, a representative oxide of graphene, is a mixture of sp2 and sp3 hybridized carbon atoms with a thin layer of graphite covalently attached with oxygen-containing functional groups [101]. Functional groups that consist of oxygen have the advantage of being easily dispersed in water and capable of interacting with different inorganic and organic materials [102]. Several studies have confirmed that synthesized GO shows excellent biocompatibility, cell adhesion, and proliferation [103, 104]. However, depending on the ambient humidity of the GO and the proportion of oxide, the conductivity and the physical properties can be restricted. To overcome these shortcomings, researchers have adopted the reduced form of GO (rGO) to partially recover the physical and electrical properties. rGO is superior to GO in conductivity and biocompatibility in the process of detecting enzyme-based reactions [105]. Although GO and rGO are very likely to be utilized in the field of tissue engineering as the main material adopted for synthesizing the conductive hydrogel for specific biocompatibility and conductivity, the relatively low conductivity and physical properties of GO and rGO can be a challenge in practical applications.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at *Polymers* **2018**, *10*, 1078; doi:10.3390/polym10101078

CNTs are cylindrical carbon tubes with nanometer diameters with a large aspect ratio. CNTs are generally manufactured by laser cutting, arc discharge, or chemical vapor deposition. Since a metal catalyst, such as, nickel can be utilized for the growth process of CNTs, nitric acid-containing oxidants are generally refined with CNTs for biological applications, which can regulate the chemical composition of CNT surfaces by making carboxylic acid groups at the terminal CNT end.

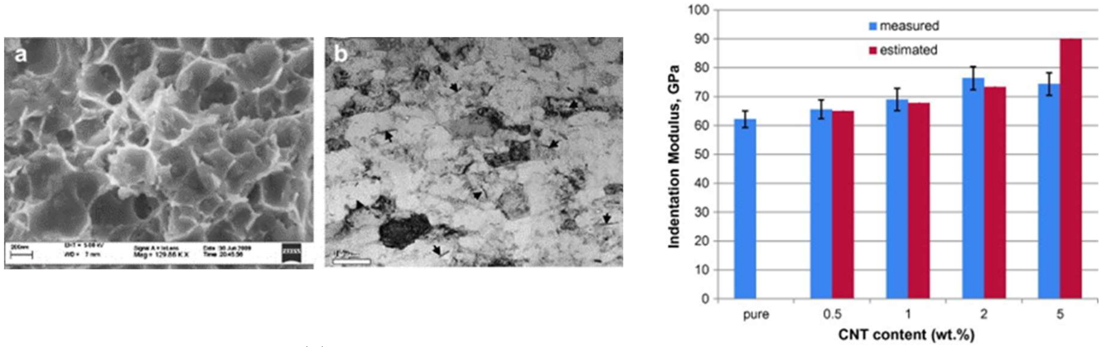
Table 3. Bulk Properties of Carbon Materials

Kinds of Carbons	Conductivity ($mS \cdot cm^{-1}$)	Advantages	Disadvantages	Application
Graphene	$10^8 \sim 10^9$	- High mechanical strength - High conductivity - Easy synthesis	- Oxidative stress - Serious aggregation - Toxicity - Hydrophobicity	Solar cells, LED, touch panels, capacitors, transistors, batteries, electrode, tissue engineering
Graphene Oxide	Depend on oxidation and humidity ($10^{-1} \sim 10^{-5}$)	- Biocompatibility - Hydrophilicity - Interacting with various inorganic and organic materials - Controllable electrical / optical properties	- Low conductivity (or even insulator) - Sensitive to humidity - Weak mechanical strength	Water purification, Coating, DNA analysis, Electrode, Optical lens, Tissue engineering
Carbon Nanotube (CNTs)	$10^7 \sim 10^8$	- High mechanical strength - High conductivity - Magnetic property	- Oxidative stress - Toxicity - Hydrophobicity - Additional synthesis step	Structural enhancement, Wire materials, Super capacitor, High-performance catalysis, Tissue engineering

CNTs are commonly utilized in biomedical applications (Figure 8) because of their high aspect ratio, low density, and electrical and physical properties [106-111]. Zhang et al. investigated the interaction between cells and modified multi-walled carbon nanotubes (MWCNTs) for biomedical applications [112]. In this study, the cell viability of human osteoblast MG-63 cells was increased by up to 67.23%. According to the results of several in vitro studies, however, CNTs can have cytotoxicity because of their inducement of oxidative stress [113] and their structure [114]. It has been reported that HeLa cells treated with functionalized single-walled carbon nanotubes (SWCNTs) and MWCNTs reduced the number of cells by 50% [115]. Nonetheless, approaches to mitigate toxicity have been discussed to exploit the advantages of CNTs. CNTs are still a promising material to produce conductive hydrogels because they increase their strength and conductivity.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at *Polymers* **2018**, *10*, 1078; doi:10.3390/polym10101078



(**a**) (**b**)

Figure 8. CNTs are suitable for strength reinforcement (a) SEM image of surface of an Al–2 wt% CNT and TEM image of an Al–2 wt.% CNT showing dispersed CNTs (indicated by arrows) within the Al matrix. (b) Effect of CNT content and estimated modulus values in the indentation modulus of investigated composites. (reproduced with permission from [109])

2.1.4. Hybrid Materials

The conductive materials for imparting conductivity to hydrogels utilized for tissue engineering have some problems. Studies on conductive hydrogel have been conducted to overcome these problems by adopting various modifications. In particular, hybridizing multiple conductive materials improves conductivity compared to that of a single conductive material. For example, it has been confirmed that a specific proportion of CNT:graphene hybrid material has a higher conductivity than a 100% CNT or graphene material [116].

Wang et al. synthesized PPy-PT-Au with multifunctional conductive hydrogel in glucose oxidase for the high sensitivity detection of tumor markers (Figure 9) [51]. In this experiment, an amperometric immunoassay for enolase (NSE) was identified as a label-free tumor marker neuron by binding to a hydrogel and resulted in a high detection limit ranging from 100 pg·mL^{-1} to 1 pg·mL^{-1}. Li et al. synthesized a cylindrical Au/graphene hydrogel under hydrothermal conditions through the self-assembly of catalyst reduction of 4-nitrophenol (4-NP) that was about 90 times higher catalyst performance than the AuNP sponge type and exhibited 14 times the increased catalyst performance compared with an AuNP catalyst-based polymer [117] It promoted electron absorption by 4-NP molecules by the high adsorption power of graphene 4-NP and electron transfer of graphene to AuNPs.

To provide both conductivity and biocompatibility, research has been conducted to hybridize multiple substances and to confirm their effects. [118, 119]. A CNT-CP composite material can impart conductivity and show superior synergistic conductivity compared with CP and CNT, according to the results of a recent research for developing a conductive hydrogel [120]. Nevertheless, these materials have been widely used because of the high charge characteristics of CP or CNTs [121]. Conductive hydrogels composed of two or more conductive materials are expected to be very prospective in the tissue engineering field.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

Figure 9. Schematic illustration of synthesized PPy-PT-Au with multifunctional conductive hydrogel for detection of tumor markers (reproduced with permission from [51]).

2.2. Synthesis Process

Many researches have studied the combination of hydrogels with conductive materials. To provide conductivity to a hydrogel, methods such as agitation of the synthesized conductive materials in the hydrogel-forming process, synthesis in situ within the hydrogel and coating of the surface of the hydrogel have been performed [122]. Since the conducting environment provided to each cell differs depending on the method of introduction of the conductivity of the hydrogel [57], it is essential to select a method that is suitable for each cell and application.

2.2.1. Blending Process

Many cases have been experimented on conductive hydrogels in the form of conductive components dispersed in a hydrogel. Generally, pre-fabricated conductive materials are added to a polymer solution before the formation of a hydrogel. It is essential that the conductive component achieve homogeneous mixing so that the conductive path is generated in a nonconductive hydrogel network. Research of these properties has been performed because the ideal conductive hydrogel has biocompatibility with improved electrical properties and physical strength [122].

Metallic materials including micro/nanoparticles and wires made of a metal, such as, gold or silver are introduced inside hydrogels to impart electrical properties. It is important that the metallic particles incorporated in hydrogels form interconnecting pathways of particles for electron transfer without compromising the physical properties of the hydrogel [123]. Although it is difficult for a network of nanowires to control uniform distribution [124-130], conductive hydrogels with nanowires can be fabricated for a wide range of tissue engineering fields, such as pressure sensors, biosensors, and electrophysiological catheters [131-133]. Conductive materials, such as CNT and graphene can cause structural defects when mixed with polymers in the development of conductive hydrogels [121, 134]. However, since the conductive materials have mechanical strength and are nano-size, they can improve the physical properties of the hydrogel and impart conductivity [110].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

Table 3. Properties of Synthesis of Conductive Hydrogels

Methods	Advantages	Disadvantages
Blending synthesis	- Easy and simple process - No additional techniques - High reproducibility - High stability of conductivity	- Low conductivity of hydrogel - Weaken hydrogel mechanical strength - Difficulty of gelation - Heterogeneous conductivity
In situ synthesis	- Homogeneous conductivity in hydrogel - Strengthen hydrogel strength - Uniform processability - High conductivity of hydrogel - High stability of conductivity	- Additional techniques are needed - Additional step can be needed - Low reproducibility
Coating process	- High conductivity of hydrogel - Simple process - Giving Conductivity easily in various shapes of hydrogel	- Potential for coating damage - Low stability of conductivity - Heterogeneous conductivity

The utilization of high shear forces and the melting process of bonding a polymer and conductive materials has the advantage that the uniformity of the material can be improved without using a toxic organic solvent. However, in this method, since heat is applied, a heat-processible polymer should be utilized. Another method of producing a conductive hydrogel is to mix previously formed CPs with a polymer to creat the hydrogel. Xiao et al. synthesized conductive hydrogels with mechanical and electrical conductivity using polyvinyl alcohol, polyethyleneglycol (PEG), and GO nanoparticles (Figure 10) [135]. During the freezing process of the GO solution in the mixed solution, crosslinking occurred for high mechanical performance. After the 3D network structure is successfully synthesized, the polymer network formed by the dense hydrogen shows high strength and elasticity.

Meanwhile, in the process of synthesizing a conductive hydrogel based on a blending method, production difficulty is the heterogeneous aggregation of the conductive material formed in the hydrogel. For example, since CNTs tend to aggregate together because of their hydrophobic nature, it is possible that heterogeneous regions may exist in the CP and CNT in the hydrogel of the polymerized procedure [136]. Although CNTs grown in PANi showed high initial conductivity of 2.946 × 103 mS·cm^{-1} [137], the reduced electrical properties of the composite because of agglomeration is still a major issue.

Although it is advantageous to incorporate a conductive material into the hydrogel or to mix it with monomers using relatively simple blending techniques, agglomeration can be a problem between the contained water and polymer matrix. To overcome such a limitation, in situ growth is recommended. In situ growth methods improve the mechanical strength 10 times or more compared to other materials [122].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at *Polymers* **2018**, *10*, 1078; doi:10.3390/polym10101078

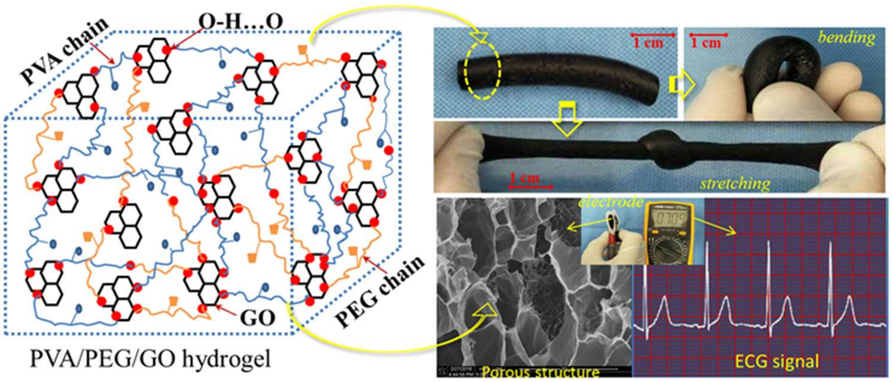


Figure 10. Polyvinyl alcohol/PEG/GO hydrogels blending with GO using the freezing thawing method (reproduced with permission from [135])/

2.2.2. In Situ Process

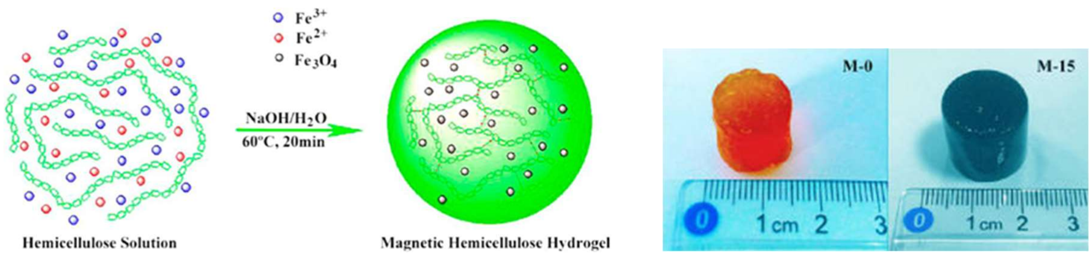
The in situ growth mechanism was introduced to provide conductivity by polymerizing the conductive component in a nonconductive hydrogel. Since such approach provides the enhanced integration of two components, it is essential to adjust the balance between the material properties, and this requires the process to be optimization for combining the new material properties. For the development of conductive hydrogels growing in situ, some techniques including the growth of metal nanoparticles in bulk hydrogels [138, 139], the deposition of CNTs through chemical vapor deposition [110], and the polymerization of conductive polymers have been performed [140].

The process of forming an in situ conductive material in a hydrogel is dependent on the type of materials. Metal particles tend to grow into nanoparticles mainly from the form of ions. Before the conductive particles are formed in the hydrogel, the degree of ion dispersion can be an important factor for producing a hydrogel with homogeneous conductivity. Zhao et al. reacted Fe3O4 nanoparticles preferentially mixed with a hemicellulose solution in the state of Fe3+ or Fe2+ ions and homogeneously produced with an NaOH solution at 60°C to form a hydrogel (Figure 11) [141]. The content of the Fe3O4 nanoparticles controlled the thermal stability, macroscopic structure, swelling behavior, and magnetization of the hydrogel. The in situ preparation of CNTs and polymer composites homogeneously distributes CNTs throughout the hydrogel and increases the weight fraction of the CNTs without impairing the mechanical strength of the hydrogel and enables excellent mixing. For example, the force transfer from the CNTs to the polymer constituting the hydrogel is affected by the homogeneity of the CNTs [134, 142, 143].

It is important to generate sites in the hydrogel for nucleation support and the subsequent growth of conductivity elements [144]. Since these elements have the property of forming at the lowest energy-cost position [144-146], spontaneous homogeneous nucleation can generally be precipitated on one side of a substrate as it is, affected by gravity during the heat or photopolymerization process or by electrical adsorption. Therefore, when the conductive polymer nuclei are formed and synthesized at the lowest energy cost, the process is necessary to grow a continuous long polymer chain homogeneously to form a conductive film [147].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

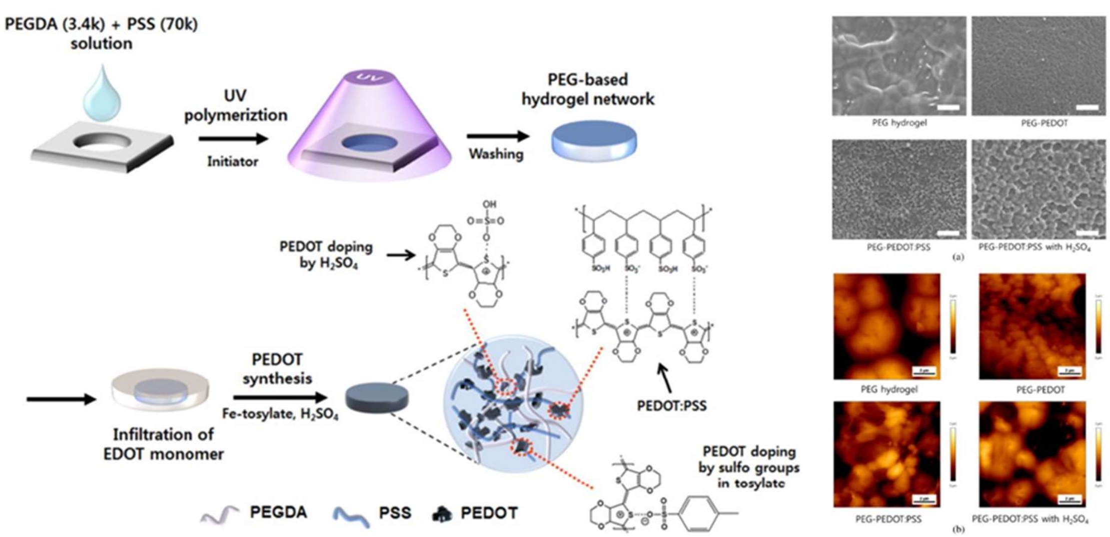


(**a**) (**b**)

Figure 11. Fe3O4 nanoparticles synthesized in situ. (a) Proposed fabrication of magnetic field-responsive hemicellulose hydrogels in basic media. (b) Prepared hemicellulose hydrogel (M-0) and magnetic-responsive hemicellulose hydrogel (M-15) (reproduced with permission from [141]).

It is usually difficult to maintain the consistency of a structure when generating an interpenetrating network between a conductive polymer and a hydrogel [146]. However, incorporating additional substances can further enhance the conductivity in the process of in situ synthesis of conductive hydrogels. Kim et al. synthesized PEDOT-PEGDA hydrogels with high conductivity and moisture contents using PSS-PEDOT (Figure 12) [148]. The incorporation of PSS in a PEG hydrogel promoted the in situ synthesis of PEDOT in the hydrogel to produce a hydrogel with increase in conductivity that was further enhanced by H2SO4 treatment.

Conductive hydrogels produced by in situ technology have the merit of producing hydrogels of high conductivity, flexibility, and considerable strength. Nevertheless, continuous research is necessary to solve the problem of devising a stable material with high reproducibility.



(**a**) (**b**)

Figure 12. Conductive PEDOT-PEGDA hydrogels using PSS-PEDOT (a) scheme of synthesizing conductive hydrogels and (b) surface morphology of PEG hydrogel, PEG-PEDOT, PEG-PEDOT : PSS, and PEG-PEDOT : PSS treated with H2SO4 (reproduced with permission from [148]).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

2.2.3. Coating Process

One method that can easily provide conductivity to a hydrogel is to coat the surface of the hydrogel. This method makes it possible to produce electrically conductive hydrogels with appropriate customized physicomechanical properties by utilizing the flexible manufacturing and processing techniques used for the polymers making up the hydrogel. The electrically conductive materials are coated on to the surface of the hydrogel, resulting a thin layer of less than 50 μm [151]. The surface coating is conducted by various chemical reaction methods including click chemistry, reversible split chain transfer, and spinner vision on the surface of the hydrogel material.

It is crucial that the polymer coating has sufficient interaction and bonding with the two components at the upper interface to prevent peeling. The bonding layer at the interface is chemically bonded, making it more stable than that using a deposition process or simple absorbance. Mechanical interlocking can also be achieved by roughening or organizing the surface of the hydrogel. Xie et al. showed that by forming a hydrogel fiber bundle, it is possible to form a conductive air guiding structure by coating a conductive polymer on its surface [152]. In this experiment, since there was sufficient mechanical bonding between the surface of the fiber nanoscale mat and PPy, peeling off of the coating was not indicated, and the electrochemical properties were similar to that of PPy macromolecules.

The coating of a laminated structure has mechanical properties different from the target hydrogel of the coating. Since the substances constituting the hydrogel and the components of the coating material act somewhat independently, it is possible that components with low elasticity may peel off or cracks may occur [153]. It is therefore essential to confirm the change in conductivity owing to the deformation of the coated hydrogel. Annibi et al. designed biocompatible and stretchy hydrogels with mechanical, biological, and electrical properties that were adjustable based on the recombinant human tropo-elastin and GO nanoparticles [154]. This fabricated hybrid material showed excellent restoring force against periodic tension and twisting forces, thereby allowing current conductivity. In addition, it was not only successfully used in the connection part of the operation of abdominal muscle, but also supported the growth and function of conductive materials and higher activity compared to pure hydrogels.

Despite the difficulty of providing a stable hydrogel coating, surface coatings have essential advantages of bioactive interface and drug delivery. Conductive layers bonded to the surface are available for surfaces that are exposed to cells that require biomolecules, such as, growth factors and cell adhesion proteins. This is integrated with the materials that make up the biocompatible hydrogel, and diffusion may proceed to be transmitted to cells. Luo et al. developed a method for producing PPy by using controlled nano-porous structures to release controlled dexamethasone in response to an electric current [155]. Wang et al. prepared an electrodeposited AuNP conductive hydrogel by adopting a crosslinking method using 1,3,5-benzenetricarboxylic acid as a ligand and Fe^{3+} as a metal ion (Figure 13) [156]. The immunosensor of the synthesized conductive hydrogel had a wide linear detection range of $1 pg \cdot mL^{-1}$ to $200 ng \cdot mL^{-1}$ and was an excellent immunoassay.

Conductive coatings have a variety of advantages associated with the delivery of drugs including bioactive agents. However, they have limitations in terms of peeling and mechanical differences associated with the interface between the coating and the hydrogel. Therefore, studies should be conducted to overcome this problem.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

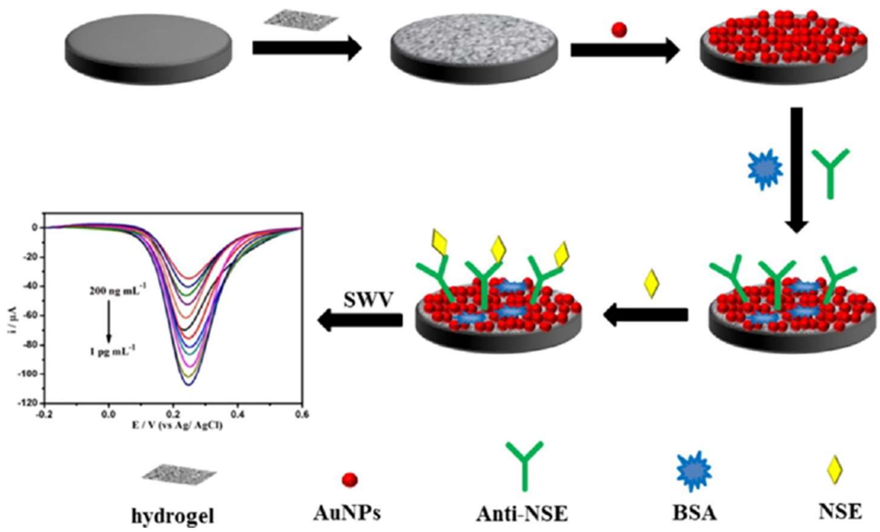


Figure 13. AuNPs electrodeposited conductive hydrogel by adopting a crosslinking method using 1,3,5-benzenetricarboxylic acid as a ligand and Fe3+ as a metal ion was synthesized. The immunosensor of the synthesized conductive hydrogel had a wide linear detection range of 1 pg·mL^{-1} to 200 ng·mL^{-1} and had excellent immunoassay (reproduced with permission from [156]).

3. Biomedical Applications for Tissue Engineering

3.1. Cardiac Tissue Engineering

Cardiovascular diseases such as myocardial infarction and heart attack, occur with abnormal electrical function because of the severe loss of myocardial cells. Compared to other tissues such as bones and skins, the cardiac muscle has a markedly limited regenerative capacity. When myocardial tissue becomes damaged, it forms a fibrotic scar tissue with a permanent loss of myocardial tissue. Many researchers have explored application plans that mimic cardiac tissue, for example, the development of biomimetic scaffolds. Since cardiomyocytes and related progenitor cell populations have been shown to grow exponentially and migrate well by electrophysiological stimulation, conductive hydrogels have been introduced into the applications of tissue engineering to mimic the intrinsic properties of such a cardiac cell environment.

Li et al. synthesized conductive hydrogels with interpenetrating network (IPN) based on carboxymethyl-chitosan and gelatin-graft-polyaniline using an in situ method [141]. In this experiment, the hydrogel was crosslinked with oxidized dextran via Schiff's base under physiological conditions and increased the storage modulus significantly. The synthesized conductive hydrogel was able to improve cell adhesion and proliferation of C2C12 cells and adipose-derived MSCs, resulting in excellent mechanical properties and biocompatibility. Yang et al. developed a homogeneous electron conducting dual network (HEDN) consisting of a rigid hydrophobic conductive network of chemically crosslinked poly (thiophene-3-acetic acid) and a flexible hydrophobic network of photographic crosslinking methacrylated aminated gelatin [157]. In this experiment, the Young's modulus of the HEDN conductive hydrogel was adjustable from 22.7 to 493.1 kPa according to the network ratio. Furthermore, the conductivity had a 10^{-1} mS·cm^{-1}, similar to the reported conductivity range of myocardial tissue. Their biological assessment confirmed that brown adipose-derived stem cells survived and proliferated on the HEDN-conducting hydrogel and improved cardiac differentiation efficiency.

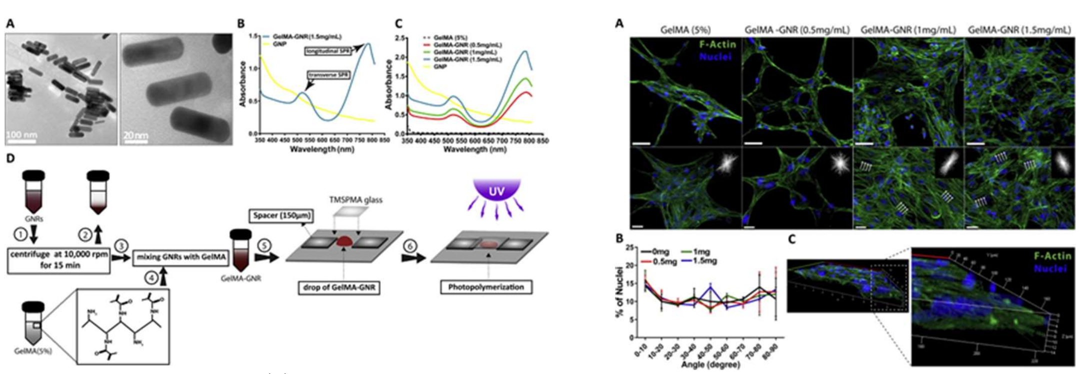
In general, composites composed of conductive hydrogels need to promote tissue formation under mechanical stimulation while providing appropriate electrochemical signals in a variety applications of cardia tissue engineering [158]. Therefore, the stability of the material must be guaranteed to be applicable for the human body. Despite the fact that PANi is biocompatible with the conductive matrix of cell cultures, the deficiency of biodegradability can lead to chronic inflammation in prolonged implantations [159]. However, PANi and its derivatives have been

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1
Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

successfully adopted because of their high stability and conductivity in the field of biomedical applications. Hosseinzadeh et al. researched a polyacrylic acid (PAA) based conductive hydrogel by using aniline polymerization based on Au nanoparticles homogeneously [160]. The Young's conductive gels were more similar to myocardium, and neonatal rat cardiomyocytes showed an increased expression of connexin 43.

In addition to the deformation of the physicochemical properties of conductive mixed material complexes, the strength of a hydrogel and electrochemical activity are also critical parameters that promote cardiac cell activity. The design of a conductive hydrogel that mimics natural extracellular matrix (ECM) characteristics requires consideration of both electrical activity and mechanical strength. Jo et al. synthesized a graphene conductive hydrogel comprised of reduced GO and polyacrylamide (PAAm) [161]. Reduced hydrogel (r(GO-PAAm)) has an elastic modulus of approximately 50kPa, which is the same strength as muscle tissue. In addition, an in vitro experiment of C2C12 myoblast showed a significant increase in proliferation and root differentiation when compared to a PAAm hydrogel. To provide a mixture of conductivity and bioactivity, Annabi et al. devised a conductive hydrogel integrated with GO nanoparticles and a highly elastic methacryloyl-substituted tropoelastin based hydrogel [154]. In this experiment, GO nanoparticles imparted conductivity while improving the toughness and elasticity of the treated hydrogel. The improved elasticity of GO particles occurred because of polymer chains and hydrophobicity, hydrogen bonds, and electrostatic interactions between the polymer chains and GO nanoparticles. In addition, the synthesized conductive hydrogel supported active growth and maturation, encouraging the growth and functionality of neonatal rat cardiomyocytes. Many studies have confirmed that conductive hydrogel is biocompatible by successfully transplanting it into rats without causing high inflammatory reactions.

Metal nanoparticles have been practically utilized as a conductive hydrogel for cardiac tissue regeneration for improving mechanical properties and biocompatibility. Metal nanoparticles can easily tune the mechanical and electrical properties of a hydrogel depending on their concentration and materials. It is important for myocardial research to synthesize these tunable conductive hydrogels because of the similarity of myocardial cell surroundings. Ahadian et al. devised a conductive GelMA using a palladium-based metallic glass submicron line (PdMGSMW) to increase the mechanical strength [162]. Conductive GelMA-PdMGSMW hydrogel can be varied depending on the concentration of the submicro lines in a hydrogel, which allows for more effective adhesion of C2C12 cells and root canal formation contraction. Navaei et al. developed a GelMA conductive hydrogel containing a UV-crosslinked gold nanorod (GNR) with improved biological and mechanical properties for cardiovascular tissue engineering (Figure 14) [163]. GNR improved the mechanical strength and conductivity of hydrogels. In addition, myocardial cells seeded with GNR-GelMA hydrogel showed excellent cell retention, cell adhesion, and viability. GNR-GelMA also supported myocardial cell beating at concurrent tissue levels.



(a) (b)

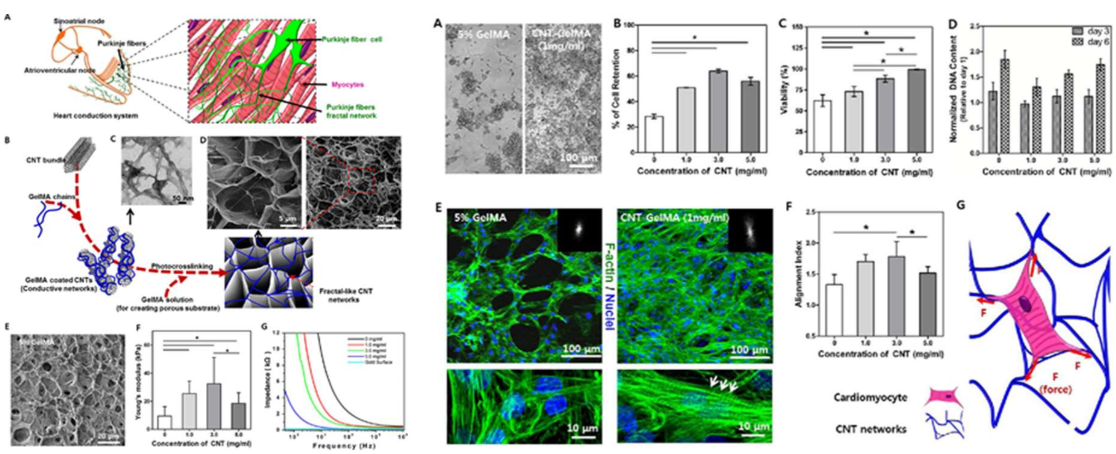
Figure 14. (a) Synthesis and characterization of GNR and GNR-GelMA hybrid hydrogels and (b) Nuclei alignment and F-actin cytoskeleton organization of cardiomyocyte in GelMA only and GelMA-GNR hydrogels (reproduced with permission from [163]).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

As described above, the conductive composites containing CNTs have emerged as functional materials in cardiac tissue engineering. For example, CNTs can be aligned in a gelatin methacryloyl (GelMA) hydrogel by using a dielectriophoresis method [164] that allows the hydrogel to provide accurate and adjustable electrical pulse stimulation to cells and tissues. Mouse embryoid bodies were cultured in microwells containing conductive hydrogels with CNTs. This conductive hydrogel enhanced the cardiac differentiation of embryoid bodies when compared to a GelMA only and a random CNT-GelMA hydrogel. Therefore, the conductive hydrogel can provide an electrically efficient and adjustable cell growth platform. In addition, CNTs can be applied to electron-emitting fibrous polymers to improve mechanical strength [165]. Shin et al. synthesized functional cardiac patches by seeding neonatal rat cardiomyocytes on CNT-incorporated photo crosslinkable gelatin methacrylate (GelMA) hydrogels (Figure 15) [166]. In this study, the electrically conductive networks within a porous gelatin framework utilized by CNTs showed an improvement in cell-cell coupling and adhesion of cardiac cells. These results proved that the incorporation of CNTs into biomaterials can be exploited to create multifunctional cardiac scaffolds for therapeutic purposes and in vitro studies.

For the study of myocardial tissue, it is necessary to consider a conductive hydrogel that can satisfy both the mechanical strength and the conductivity that mimic the cardiac circumstances and can withstand the heartbeat. Therefore, conductive hydrogels used in myocardial tissue have been improvised to satisfy the needs of mechanical strength and conductivity.



(a) (b)

Figure 15. (a) Successfully synthesized CNT-GelMA conductive hydrogel and (b) improved cardiac cell adhesion and alignment on CNT-GelMA. In this study, CNTs improved cell-cell coupling and cardiac cell adhesion (reproduced with permission from [166]).

3.2. Nerve Tissue Engineering

Damaged nervous tissue can be treated artificially if the depth of injury is so deep that it is difficult to recover by self-sustenance and will permanently damage a body's function. Researchers have studied nerve tissue lesions using various strategies. The commercialized treatment method for treating nerve tissue defects is to transplant autografts, allografts, or xenografts to lesions. However, these treatment methods can increase the prevalence of the donor site and evoke an immune-rejection reaction. Therefore, researchers have devised hydrogels that can be used for tissue engineering for nerve tissue regeneration to complement the disadvantages of existing transplantation treatments. Various studies have demonstrated that a conductive environment promotes neuronal proliferation and differentiation by providing an environment around nerve tissue of electrical signal exchange and conduction properties.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at *Polymers* **2018**, *10*, 1078; doi:10.3390/polym10101078

In addition, it is essential to test the biocompatibility and conductivity of various conductive hydrogels in nervous tissue engineering applications. Shi et al. prepared an in situ conductive nanoporous hydrogel by coating nanoporous cellulose gels (NCG) with PPy nanoparticles from pyrrole monomers [167]. The resulting NCG-PPy conductive hydrogel showed a conductivity of 80 mS·cm^{-1}. In vitro studies have shown that adhesion of PPy to NCG improved adhesion and proliferation of PC12 cells and showed that the PPy-NCG hydrogel induced neurite outgrowth and had excellent biocompatibility. Bu et al. introduced a method of synthesizing conductive sodium alginate, PPy, and carboxymethyl chitosan (CMCS) polymer hydrogels to aid in peripheral nerve regeneration (Figure 16) [168]. The calcium ion crosslinked sodium alginate/CMCS hydrogels provided by the sustained release system consisting of D-glucono-D-lactone and ultrafiltered calcium carbonate (CaCO3) were coated with PPy particles. The swelling ratio, gelation time, elastic modulus, and porosity of the conductive hydrogel were adjusted according to the content of PPy. The conductivity of the synthesized sample was 2.41 mS·cm^{-1}. The prepared conductive hydrogel showed high biocompatibility and cell adhesion and proliferation by culturing PC12, RSC96, and bone marrow derived mesenchymal stem cells (BMMSCs). In vivo studies confirmed that conductive hydrogel has biocompatibility through subcutaneous inflammatory reactions and can act as a supplement in the nerve conduit. Yang et al. synthesized a conductive PPy/alginate hydrogel by polymerizing PPy chemically in an ionically crosslinked alginate hydrogel [169]. In this study, the cell adhesion and growth of human bone marrow-derived mesenchymal stem cells in PPy/alginate hydrogel were promoted. In addition, the PPy/alginate hydrogels enhanced the expression of neural differentiation markers of human bone marrow-derived mesenchymal stem cells, including Tuj1 and MAP 2 relative to control groups. This study showed that conductive hydrogel can be useful in providing mechanical and electrical signals to stem cells and nerve cells.

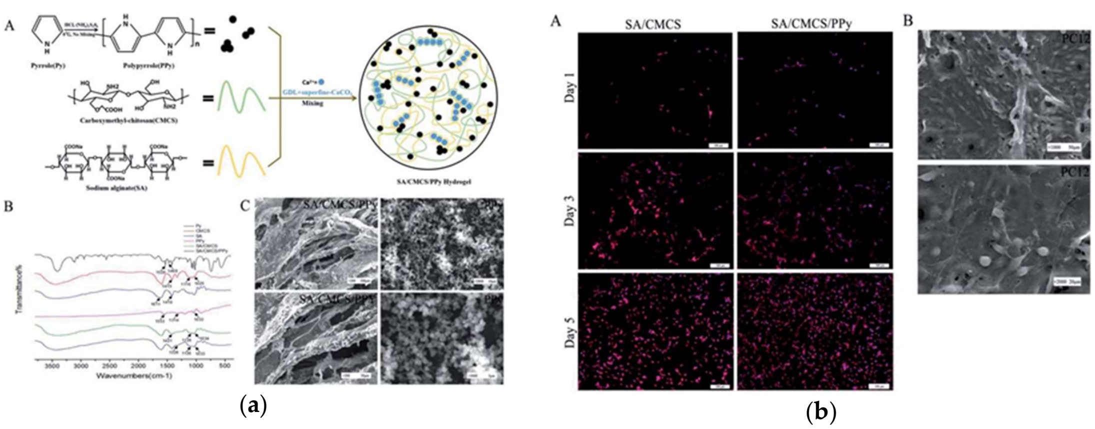


Figure 16. Conductive sodium alginate, PPy, and CMCS hydrogels to aid in peripheral nerve regeneration. (a) Sodium alginate/CMCS/PPy hydrogel was successfully synthesized and (b) PC12 cells on sodium alginate/CMCS and sodium alginate/CMCS/PPy hydrogel. PC12 cells grew well and adhered to sodium alginate/CMCS/PPy more effectively compared to the control sample (reproduced with permission from [168]).

The nerve ECM has various conductivities from peripheral nerve tissues to cerebral cortex tissues [119]. In neural tissue engineering, research has shown the necessity of producing conductive hydrogels that can easily change conductivity corresponding to the different electrical environments of nerve tissues. Xu et al. synthesized a conducting complex nerve conduit with PPy and poly (d, l-lactic acid) and evaluated its capability to carry the differentiation of rat pheochromocytoma 12 (PC 12) cells in vitro, which determined the ability to encourage nerve regeneration in vivo [170]. Depending on the PPy content of the produced nerve conduit, the conductivity was in the range of 15.56 ms·cm^{-1} to 5.65 ms·cm^{-1}. PC12 cells were seeded in the conduits and showed an increase in both the neurite-bearing cell proportion and central neurite length. Liu et al. devised an

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

rGOaCNTpega-OPF-MTAC hydrogel with a positive charge and conductivity that passed the positive charge to 2-(methacryloyloxy) ethyltrimethylammonium chloride (MTAC) and chemically crosslinked it to GOa and CNTpega in an oligo (poly(ethylene glycol) fumarate) (OPA) hydrogel [171]. The conductivity of the hydrogel increased step by step during the process of synthesizing the hydrogel. The final conductivity was approximately (5.75 ± 3.23) × 10-2 $mS \cdot cm^{-1}$. Biological evaluation also showed a spread of PC12 cells on the conductive hydrogel, which was confirmed by the strong neurite outgrowth of cells on the conductive hydrogel induced during the differentiation process after growth factor treatment. A polyurethane hybrid composite was devised using PSS doped PEDOT and liquid crystal GO, a polyether-based liner polyurethane and the conductive hydrogel obtained high biocompatibility, conductivity, and flexibility [172]. The synthesized polyurethane hybrid composite conductive hydrogel showed 10-times higher conductivity, 1.6-times higher tensile modulus, and 1.56-times the yield strength than a control group. It also supported human neural stem cells growth and the differentiation of neurons. It was confirmed that the produced hydrogel secured biocompatibility, high flexibility, and conductivity.

Conducting materials used in neural tissue studies require mechanical strength, biocompatibility, and the ability to control the conductivity of the surrounding neural tissues. Conductive hydrogels of neural tissues need to focus on different biocompatibility and conductivities depending on the location of various neurological lesions.

3.3. Bone Tissue Engineering

Bone tissue engineering undergoes a process initiated by the migration and recruitment of bone origin cells. It is then followed by proliferation, differentiation, and matrix formation [173]. Generally, bone tissue engineering materials requires high mechanical strength of osteoconductive characteristics [174]. However, hydrogel has a low mechanical strength and needs to improve its mechanical properties to mimic bone tissue.

The conductive material in a hydrogel should be able to increase the effect of bone conduction and mechanical strength. Gold nanoparticles (GNPs) are known to be the most promising substances for bone tissue regeneration because they promote osteogenic differentiation of MSCs [175]. Heo et al. synthesized biodegradable hydrogel using GNPs and regenerated bone tissues [176]. The hydrogel contained GNPS in a gel via UV-induced chemical crosslinking using GelMA. The cell experiment showed that the conductive GNP hydrogel significantly increased the activity, proliferation, and bone formation, especially in animal experiments. To increase the elastic modulus, roughness, and conductivity, the incorporation of conductive fibers using graphene nanoparticles and PANi into a hydrogel was devised [177]. In cell experiments, the conductive hydrogel-fiber complex retained similar cell adhesion, proliferation, and morphology to human osteoblasts than did a non-conductive hydrogel. Ezazi et al. developed a skeletal hydrogel containing hydroxyapaptite, gelatin, and mesoporous silica [178]. This hydrogel was conjugated with PPy macromolecules to confer conductivity and vancomycin and an antibiotic model was loaded. The support containing PPy showed superior mechanical properties and a higher proportion of protein than that of the nonconductive support. Even the in vitro experiments confirmed that the osteoblastic cells were contained in gelatin matrix and had survived for 14 days.

To fabricate a conductive hydrogel to be utilized in bone tissue engineering, it is easy to provide an increase in strength and conductivity by coating the already-hardened hydrogel surface. Pelto et al. demonstrated that PPy-coated PLA scaffolds promote cell growth of adipose-derived stem cells for bone tissue regeneration via physiochemical signaling [179]. A symmetric biphasic pulsed DC voltage of 0.2V for 4h at 1 Hz significantly enhanced an adipose-derived stem cell in vitro culture after 14 days. Therefore, the supply of intrinsic conductivity and electrical stimulation of a CNT material provides an overall effect that promotes the osteogenic differentiation of stem cells and regulates the activity of cells indispensable for the regeneration of bone tissue.

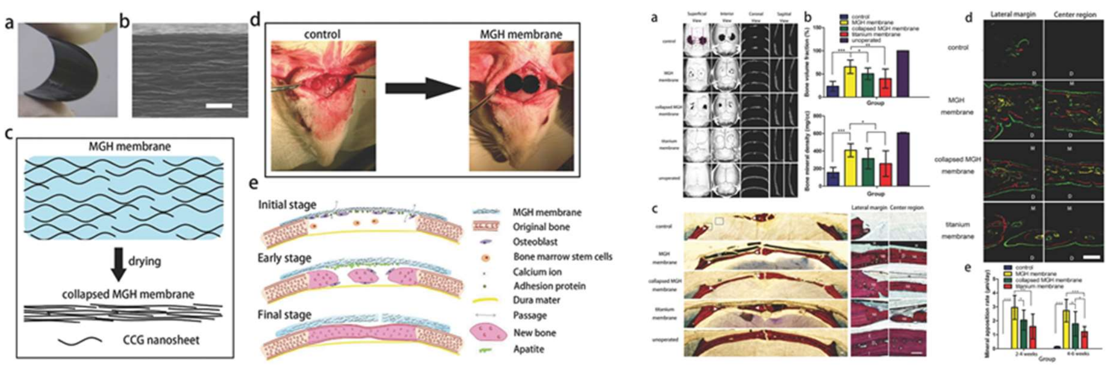
However, provide conductivity for regenerating bone tissue, research have been conducted to simultaneously improve mechanical strength and conductivity of a biodegradable hydrogel using

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 August 2018 doi:10.20944/preprints201808.0280.v1

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

conductive materials. Lu et al. synthesized a multilayered graphene hydrogel as a reference to utilize in bone regeneration (Figure 17) [180]. It was proved that the chemically synthesized graphene-based hydrogel properly maintained osseous space and promoted early osteogenesis. In addition, the graphene hydrogel improved the mechanical strength, flexibility, and adhesion of osteoblast and bone tissues. Chen et al. developed a conductive nano-PLA scaffold with well-dispersed PANi nanostructures that promoted osteogenic differentiation and combined the properties of 3D matrices [181]. The scaffold structure and content of polyaniline nanoparticles formed through in situ were confirmed, and bone MSCs derived after three weeks were cultured on a composite support. As a result, it was confirmed that expression levels of alkaline phosphatase, osteocalcin and runt-related transcription factors of bone MSCs on the composite support increased.

As mentioned above, the conductive hydrogel in the osteocyte study investigated the porous structure by securing adequate conductivity and providing the same environment as osteocytes. This can be a key factor of research on conductive hydrogels to significantly promote osteogenic differentiation by providing an environment of structural conductivity.



(a) (b)

Figure 17 (a) Multilayered graphene hydrogel reference for bone regeneration. (b) Graphene hydrogel improved the physical properties of mechanical strength and flexibility, and showed improved adhesion on osteoblast and bone tissues (reproduced with permission from [180]).

4. Conclusion and Future Perspectives

This review focused on performing a variety of assessments of conductive materials, manufacturing methods of the conductive hydrogel, and applications for the biomedical area based on studies reported in various papers. Most initial studies on conductive hydrogels focused on evaluating whether conductive materials can be adequately used in the biomedical field. Conductive materials with low mechanical properties, low processability, and bad biocompatibility that are not compatible with in vivo were adopted to hydrogel manufacturing technology using existing verified materials, resulting in the synthesis of a conductive hydrogel that simultaneously possessed the strength of a hydrogel and conductivity. The importance of an electrically conductive material combined with the proper blending technique and manufacturing method is the key to developing a useful composite hydrogel suitable for applications in the biomedical field. Although this approach can solve the processability and mechanical properties of reduced electrical conductivity and interactions between hydrogels and conducting polymers, the application range of these hydrogels is restricted.

In many reported types of research, the biocompatibility testing of conductive hydrogels has been limited to in vitro screening. It is necessary to develop a material constituting conductive hydrogels so that it can be applied to actual patients through proper functional animal research before being used in the field of clinical applications. It is apparent that this is a promising application field since the conductive hydrogel synthesized via a conductive material can be provided to tissue that requires electrical stimulation in the body such as nerve detection and stimulation, regeneration of muscular cells, and as a biological electrode in the body. However,

Peer-reviewed version available at *Polymers* **2018**, *10*, 1078; doi:10.3390/polym10101078

many technical challenges have yet to be solved in this field, and many opportunities are available for researchers to develop hydrogels with strength and conductivity suitable for use.

Acknowledgment

This work was supported by the National Research Foundation (NRF) grant funded by the Ministry of Science, ICT (MSIT) (2015R1D1A1A01060444 and 2018M3A9E2024583)

References

1. Atala, Anthony, F. Kurtis Kasper, and Antonios G. Mikos. "Engineering Complex Tissues." Science Translational Medicine 4, no. 160 (2012): 160rv12-60rv12.
2. Gaharwar, Akhilesh K, Nicholas A Peppas, and Ali Khademhosseini. "Nanocomposite Hydrogels for Biomedical Applications." Biotechnology and bioengineering 111, no. 3 (2014): 441-53.
3. Balint, Richard, Nigel J Cassidy, and Sarah H Cartmell. "Conductive Polymers: Towards a Smart Biomaterial for Tissue Engineering." Acta Biomaterialia 10, no. 6 (2014): 2341-53.
4. Kloxin, April M, Christopher J Kloxin, Christopher N Bowman, and Kristi S Anseth. "Mechanical Properties of Cellularly Responsive Hydrogels and Their Experimental Determination." Advanced Materials 22, no. 31 (2010): 3484-94.
5. Yang, Xiaowei, Ling Qiu, Chi Cheng, Yanzhe Wu, Zi-Feng Ma, and Dan Li. "Ordered Gelation of Chemically Converted Graphene for Next-Generation Electroconductive Hydrogel Films." Angewandte Chemie International Edition 50, no. 32 (2011): 7325-28.
6. Dhandayuthapani, Brahatheeswaran, Yasuhiko Yoshida, Toru Maekawa, and D. Sakthi Kumar. "Polymeric Scaffolds in Tissue Engineering Application: A Review." International Journal of Polymer Science 2011 (2011): 1-19.
7. Straley, Karin S., Cheryl Wong Po Foo, and Sarah C. Heilshorn. "Biomaterial Design Strategies for the Treatment of Spinal Cord Injuries." Journal of Neurotrauma 27, no. 1 (2010): 1-19.
8. Mirkin, C. A. "The Beginning of a Small Revolution." Small 1, no. 1 (2005): 14-6.
9. Campelo, J. M., D. Luna, R. Luque, J. M. Marinas, and A. A. Romero. "Sustainable Preparation of Supported Metal Nanoparticles and Their Applications in Catalysis." ChemSusChem 2, no. 1 (2009): 18-45.
10. Abdullah, Mikrajuddin, Khairurrijal Khairurrijal, Abdul Rajak, Riri Murniati, and Elfi Yuliza. "Effect of Particle Size on the Electrical Conductivity of Metallic Particles." In Proceedings of the 2014 International Conference on Advances in Education Technology, 2014.
11. Otsuka, Hidenori, Yukio Nagasaki, and Kazunori Kataoka. "Pegylated Nanoparticles for Biological and Pharmaceutical Applications." Advanced drug delivery reviews 64 (2012): 246-55.
12. Ayush, Verma, and Stellacci Francesco. "Effect of Surface Properties on Nanoparticle–Cell Interactions." Small 6, no. 1 (2010): 12-21.
13. Skardal, Aleksander, Jianxing Zhang, Lindsi McCoard, Xiaoyu Xu, Siam Oottamasathien, and Glenn D Prestwich. "Photocrosslinkable Hyaluronan-Gelatin Hydrogels for Two-Step Bioprinting." Tissue Engineering Part A 16, no. 8 (2010): 2675-85.
14. Ruirui, Xing, Liu Kai, Jiao Tifeng, Zhang Ning, Ma Kai, Zhang Ruiyun, Zou Qianli, Ma Guanghui, and Yan Xuehai. "An Injectable Self-Assembling Collagen–Gold Hybrid Hydrogel for Combinatorial Antitumor Photothermal/Photodynamic Therapy." Advanced Materials 28, no. 19 (2016): 3669-76.
15. Xu, Liming, Xuefei Li, Taro Takemura, Nobutaka Hanagata, Gang Wu, and Laisheng Lee Chou. "Genotoxicity and Molecular Response of Silver Nanoparticle (Np)-Based Hydrogel." Journal of Nanobiotechnology 10, no. 1 (2012): 16.
16. Paquet, Chantal, Hendrick W. de Haan, Donald M. Leek, Hung-Yu Lin, Bo Xiang, Ganghong Tian, Arnold Kell, and Benoit Simard. "Clusters of Superparamagnetic Iron Oxide Nanoparticles Encapsulated in a Hydrogel: A Particle Architecture Generating a Synergistic Enhancement of the T2 Relaxation." ACS Nano 5, no. 4 (2011): 3104-12.
17. Zare, Maryam, Zahra Ramezani, and Nadereh Rahbar. "Development of Zirconia Nanoparticles-Decorated Calcium Alginate Hydrogel Fibers for Extraction of Organophosphorous

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

Pesticides from Water and Juice Samples: Facile Synthesis and Application with Elimination of Matrix Effects." Journal of Chromatography A 1473 (2016): 28-37.

18. Shi, Xinhao, Wei Gu, Bingyu Li, Ningning Chen, Kai Zhao, and Yuezhong Xian. "Enzymatic Biosensors Based on the Use of Metal Oxide Nanoparticles." Microchimica Acta 181, no. 1 (2014): 1-22.
19. Gutiérrez-Sánchez, Cristina, Marcos Pita, Cristina Vaz-Domínguez, Sergey Shleev, and Antonio L. De Lacey. "Gold Nanoparticles as Electronic Bridges for Laccase-Based Biocathodes." Journal of the American Chemical Society 134, no. 41 (2012): 17212-20.
20. Arvizo, Rochelle R, Sanjib Bhattacharyya, Rachel A Kudgus, Karuna Giri, Resham Bhattacharya, and Priyabrata Mukherjee. "Intrinsic Therapeutic Applications of Noble Metal Nanoparticles: Past, Present and Future." Chemical Society Reviews 41, no. 7 (2012): 2943-70.
21. Prasanthkumar, Seelam, Anesh Gopal, and Ayyappanpillai Ajayaghosh. "Self-Assembly of Thienylenevinylene Molecular Wires to Semiconducting Gels with Doped Metallic Conductivity." Journal of the American Chemical Society 132, no. 38 (2010): 13206-07.
22. Shah, Monic, Vivek Badwaik, Yogesh Kherde, Hitesh Waghwani, Tulsi Modi, Zoraida Aguilar, Hannah Rodgers, William Hamilton, Tamilselvi Marutharaj, Cathleen Webb, Matthew Lawrenz, and Rajalingam Dakshinamurthy. Gold Nanoparticles: Various Methods of Synthesis and Antibacterial Applications. Vol. 19, 2014.
23. Cho, Il-Hoon, Arun Bhunia, and Joseph Irudayaraj. "Rapid Pathogen Detection by Lateral-Flow Immunochromatographic Assay with Gold Nanoparticle-Assisted Enzyme Signal Amplification." International Journal of Food Microbiology 206 (2015): 60-66.
24. Chung, Ui Seok, Joo-Ho Kim, Byeonggwan Kim, Eunkyoung Kim, Woo-Dong Jang, and Won-Gun Koh. "Dendrimer Porphyrin-Coated Gold Nanoshells for the Synergistic Combination of Photodynamic and Photothermal Therapy." Chemical Communications 52, no. 6 (2016): 1258-61.
25. Rengan, Aravind Kumar, Amirali B Bukhari, Arpan Pradhan, Renu Malhotra, Rinti Banerjee, Rohit Srivastava, and Abhijit De. "In Vivo Analysis of Biodegradable Liposome Gold Nanoparticles as Efficient Agents for Photothermal Therapy of Cancer." Nano Letters 15, no. 2 (2015): 842-48.
26. Kennedy, Laura C, Lissett R Bickford, Nastassja A Lewinski, Andrew J Coughlin, Ying Hu, Emily S Day, Jennifer L West, and Rebekah A Drezek. "A New Era for Cancer Treatment: Gold-Nanoparticle-Mediated Thermal Therapies." Small 7, no. 2 (2011): 169-83.
27. Kang, Zhuo, Xiaoqin Yan, Lanqing Zhao, Qingliang Liao, Kun Zhao, Hongwu Du, Xiaohui Zhang, Xueji Zhang, and Yue Zhang. "Gold Nanoparticle/Zno Nanorod Hybrids for Enhanced Reactive Oxygen Species Generation and Photodynamic Therapy." Nano Research 8, no. 6 (2015): 2004-14.
28. Nossier, Ahmed Ibrahim, Sanaa Eissa, Manal Fouad Ismail, Mohamed Ahmed Hamdy, and Hassan Mohamed El-Said Azzazy. "Direct Detection of Hyaluronidase in Urine Using Cationic Gold Nanoparticles: A Potential Diagnostic Test for Bladder Cancer." Biosensors and Bioelectronics 54 (2014): 7-14.
29. Baei, Payam, Sasan Jalili-Firoozinezhad, Sareh Rajabi-Zeleti, Mohammad Tafazzoli-Shadpour, Hossein Baharvand, and Nasser Aghdami. "Electrically Conductive Gold Nanoparticle-Chitosan Thermosensitive Hydrogels for Cardiac Tissue Engineering." Materials Science and Engineering: C 63 (2016): 131-41.
30. Iravani, Siavach, Hassan Korbekandi, Seyed Vahid Mirmohammadi, and B Zolfaghari. "Synthesis of Silver Nanoparticles: Chemical, Physical and Biological Methods." Research in pharmaceutical sciences 9, no. 6 (2014): 385.
31. Durán, Nelson, Gerson Nakazato, and Amedea B Seabra. "Antimicrobial Activity of Biogenic Silver Nanoparticles, and Silver Chloride Nanoparticles: An Overview and Comments." Applied microbiology and biotechnology 100, no. 15 (2016): 6555-70.
32. Johnston, Helinor J., Gary Hutchison, Frans M. Christensen, Sheona Peters, Steve Hankin, and Vicki Stone. "A Review of the in Vivo and in Vitro Toxicity of Silver and Gold Particulates: Particle Attributes and Biological Mechanisms Responsible for the Observed Toxicity." Critical Reviews in Toxicology 40, no. 4 (2010): 328-46.
33. Rai, MK, SD Deshmukh, AP Ingle, and AK Gade. "Silver Nanoparticles: The Powerful Nanoweapon against Multidrug-Resistant Bacteria." Journal of applied microbiology 112, no. 5 (2012): 841-52.
34. Meng, Mei, Huawei He, Jing Xiao, Ping Zhao, Jiale Xie, and Zhisong Lu. "Controllable in Situ Synthesis of Silver Nanoparticles on Multilayered Film-Coated Silk Fibers for Antibacterial Application." Journal of colloid and interface science 461 (2016): 369-75.

35. Xiang, Dongxi, Yang Zheng, Wei Duan, Xiujing Li, Jianjian Yin, Sarah Shigdar, Michael Liam O'Connor, Manju Marappan, Xiaojuan Zhao, Yingqiu Miao, Bin Xiang, and Conglong Zheng. "Inhibition of a/Human/Hubei/3/2005 (H3n2) Influenza Virus Infection by Silver Nanoparticles in Vitro and in Vivo." International Journal of Nanomedicine 8 (2013): 4103-14.
36. Braun, Gary B., Tomas Friman, Hong-Bo Pang, Alessia Pallaoro, Tatiana Hurtado de Mendoza, Anne-Mari A. Willmore, Venkata Ramana Kotamraju, Aman P. Mann, Zhi-Gang She, Kazuki N. Sugahara, Norbert O. Reich, Tambet Teesalu, and Erkki Ruoslahti. "Etchable Plasmonic Nanoparticle Probes to Image and Quantify Cellular Internalization." Nature Materials 13 (2014): 904.
37. Shi, Jinjin, Lei Wang, Jing Zhang, Rou Ma, Jun Gao, Yan Liu, Chaofeng Zhang, and Zhenzhong Zhang. "A Tumor-Targeting near-Infrared Laser-Triggered Drug Delivery System Based on Go@Ag Nanoparticles for Chemo-Photothermal Therapy and X-Ray Imaging." Biomaterials 35, no. 22 (2014): 5847-61.
38. Austin, Lauren A., Megan A. Mackey, Erik C. Dreaden, and Mostafa A. El-Sayed. "The Optical, Photothermal, and Facile Surface Chemical Properties of Gold and Silver Nanoparticles in Biodiagnostics, Therapy, and Drug Delivery." Archives of Toxicology 88, no. 7 (2014): 1391-417.
39. Jeyaraj, M, G Sathishkumar, G Sivanandhan, D MubarakAli, M Rajesh, R Arun, G Kapildev, M Manickavasagam, N Thajuddin, and K Premkumar. "Biogenic Silver Nanoparticles for Cancer Treatment: An Experimental Report." Colloids and Surfaces B: Biointerfaces 106 (2013): 86-92.
40. Stepanov, AL, AN Golubev, SI Nikitin, and YN Osin. "A Review on the Fabrication and Properties of Platinum Nanoparticles." Rev. Adv. Mater. Sci 38, no. 160 (2014): e175.
41. Lee, Sanghee, Donghoon Kwon, Changyong Yim, and Sangmin Jeon. "Facile Detection of Troponin I Using Dendritic Platinum Nanoparticles and Capillary Tube Indicators." Analytical chemistry 87, no. 9 (2015): 5004-08.
42. Li, Mian, Xiangjie Bo, Zhongcheng Mu, Yufan Zhang, and Liping Guo. "Electrodeposition of Nickel Oxide and Platinum Nanoparticles on Electrochemically Reduced Graphene Oxide Film as a Nonenzymatic Glucose Sensor." Sensors and Actuators B: Chemical 192 (2014): 261-68.
43. Hikosaka, Keisuke, Juewon Kim, Masashi Kajita, Atsuhiro Kanayama, and Yusei Miyamoto. "Platinum Nanoparticles Have an Activity Similar to Mitochondrial Nadh: Ubiquinone Oxidoreductase." Colloids and Surfaces B: Biointerfaces 66, no. 2 (2008): 195-200.
44. Xie, Jin, Gang Liu, Henry S. Eden, Hua Ai, and Xiaoyuan Chen. "Surface-Engineered Magnetic Nanoparticle Platforms for Cancer Imaging and Therapy." Accounts of chemical research 44, no. 10 (2011): 883-92.
45. Xu, Qian, Jianping Li, Shuhuai Li, and Hongcheng Pan. "A Highly Sensitive Electrochemiluminescence Immunosensor Based on Magnetic Nanoparticles and Its Application in Ca125 Determination." Journal of Solid State Electrochemistry 16, no. 9 (2012): 2891-98.
46. Li, Mei, Lizhong Zhu, and Daohui Lin. "Toxicity of Zno Nanoparticles to Escherichia Coli: Mechanism and the Influence of Medium Components." Environmental Science & Technology 45, no. 5 (2011): 1977-83.
47. Zhang, Haijun, Baoan Chen, Hui Jiang, Cailian Wang, Huangping Wang, and Xuemei Wang. "A Strategy for Zno Nanorod Mediated Multi-Mode Cancer Treatment." Biomaterials 32, no. 7 (2011): 1906-14.
48. Fan, Zhiyong, and Jia G Lu. "Zinc Oxide Nanostructures: Synthesis and Properties." Journal of Nanoscience and Nanotechnology 5, no. 10 (2005): 1561-73.
49. Genchi, Giada G, Harald Nuhn, Ioannis Liakos, Attilio Marino, Sergio Marras, Athanassia Athanassiou, Virgilio Mattoli, and Tejal A Desai. "Titanium Dioxide Nanotube Arrays Coated with Laminin Enhance C2c12 Skeletal Myoblast Adhesion and Differentiation." RSC Advances 6, no. 22 (2016): 18502-14.
50. Zheng, Haitao, and Mkhulu Mathe. "Enhanced Conductivity and Stability of Composite Membranes Based on Poly (2, 5-Benzimidazole) and Zirconium Oxide Nanoparticles for Fuel Cells." Journal of Power Sources 196, no. 3 (2011): 894-98.
51. Wang, Huiqiang, and Zhanfang Ma. "A Cascade Reaction Signal-Amplified Amperometric Immunosensor Platform for Ultrasensitive Detection of Tumour Marker." Sensors and Actuators B: Chemical 254 (2018): 642-47.
52. Zhong Lin, Wang. "Zinc Oxide Nanostructures: Growth, Properties and Applications." Journal of Physics: Condensed Matter 16, no. 25 (2004): R829.
53. Gerard, Manju, Asha Chaubey, and B. D. Malhotra. "Application of Conducting Polymers to Biosensors." Biosensors and Bioelectronics 17, no. 5 (2002): 345-59.

54. Mozafari, Masoud, Mehrnoush Mehraien, Daryoosh Vashaee, and Lobat Tayebi. "Electroconductive Nanocomposite Scaffolds: A New Strategy into Tissue Engineering and Regenerative Medicine." In Nanocomposites-New Trends and Developments: InTech, 2012.
55. Rylie, A. Green, Baek Sungchul, A. Poole-Warren Laura, and J. Martens Penny. "Conducting Polymer-Hydrogels for Medical Electrode Applications." Science and Technology of Advanced Materials 11, no. 1 (2010): 014107.
56. Sajesh, K. M., R. Jayakumar, Shantikumar V. Nair, and K. P. Chennazhi. "Biocompatible Conducting Chitosan/Polypyrrole–Alginate Composite Scaffold for Bone Tissue Engineering." International Journal of Biological Macromolecules 62 (2013): 465-71.
57. Kai, Dan, Molamma P. Prabhakaran, Guorui Jin, and Seeram Ramakrishna. "Polypyrrole-Contained Electrospun Conductive Nanofibrous Membranes for Cardiac Tissue Engineering." Journal of Biomedical Materials Research Part A 99A, no. 3 (2011): 376-85.
58. Ghasemi-Mobarakeh, L., M. P. Prabhakaran, M. Morshed, M. H. Nasr-Esfahani, H. Baharvand, S. Kiani, S. S. Al-Deyab, and S. Ramakrishna. "Application of Conductive Polymers, Scaffolds and Electrical Stimulation for Nerve Tissue Engineering." J Tissue Eng Regen Med 5, no. 4 (2011): e17-35.
59. Chougule, Manik A, Shailesh G Pawar, Prasad R Godse, Ramesh N Mulik, Shashwati Sen, and Vikas B Patil. "Synthesis and Characterization of Polypyrrole (Ppy) Thin Films." Soft Nanoscience Letters 1, no. 01 (2011): 6.
60. Brezoi, DRAGOŞ VIOREL. "Polypyrrole Films Prepared by Chemical Oxidation of Pyrrole in Aqueous Fecl3 Solution." J. Sci. arts 1, no. 12 (2010): 53-58.
61. Yu, Song, Liu Tian-Yu, Xu Xin-Xin, Feng Dong-Yang, Li Yat, and Liu Xiao-Xia. "Pushing the Cycling Stability Limit of Polypyrrole for Supercapacitors." Advanced Functional Materials 25, no. 29 (2015): 4626-32.
62. Huang, Zhong-Bing, Guang-Fu Yin, Xiao-Ming Liao, and Jian-Wen Gu. "Conducting Polypyrrole in Tissue Engineering Applications." Frontiers of Materials Science 8, no. 1 (2014): 39-45.
63. Stewart, E. M., X. Liu, G. M. Clark, R. M. I. Kapsa, and G. G. Wallace. "Inhibition of Smooth Muscle Cell Adhesion and Proliferation on Heparin-Doped Polypyrrole." Acta Biomaterialia 8, no. 1 (2012): 194-200.
64. Huang, J., L. Lu, J. Zhang, X. Hu, Y. Zhang, W. Liang, S. Wu, and Z. Luo. "Electrical Stimulation to Conductive Scaffold Promotes Axonal Regeneration and Remyelination in a Rat Model of Large Nerve Defect." PLoS One 7, no. 6 (2012): e39526.
65. Abidian, Mohammad R., Eugene D. Daneshvar, Brent M. Egeland, Daryl R. Kipke, Paul S. Cederna, and Melanie G. Urbanchek. "Hybrid Conducting Polymer–Hydrogel Conduits for Axonal Growth and Neural Tissue Engineering." Advanced healthcare materials 1, no. 6 (2012): 762-67.
66. Runge, M. B., M. Dadsetan, J. Baltrusaitis, A. M. Knight, T. Ruesink, E. A. Lazcano, L. Lu, A. J. Windebank, and M. J. Yaszemski. "The Development of Electrically Conductive Polycaprolactone Fumarate-Polypyrrole Composite Materials for Nerve Regeneration." Biomaterials 31, no. 23 (2010): 5916-26.
67. Zou, Y., J. Qin, Z. Huang, G. Yin, X. Pu, and D. He. "Fabrication of Aligned Conducting Ppy-Plla Fiber Films and Their Electrically Controlled Guidance and Orientation for Neurites." ACS Appl Mater Interfaces 8, no. 20 (2016): 12576-82.
68. Tian, L., M. P. Prabhakaran, J. Hu, M. Chen, F. Besenbacher, and S. Ramakrishna. "Synergistic Effect of Topography, Surface Chemistry and Conductivity of the Electrospun Nanofibrous Scaffold on Cellular Response of Pc12 Cells." Colloids Surf B Biointerfaces 145 (2016): 420-29.
69. Zhang, Hong, Kefeng Wang, Yiming Xing, and Qiaozhen Yu. "Lysine-Doped Polypyrrole/Spider Silk Protein/Poly(L-Lactic) Acid Containing Nerve Growth Factor Composite Fibers for Neural Application." Materials Science and Engineering: C 56 (2015): 564-73.
70. Yang, Jongcheol, Goeun Choe, Sumi Yang, Hyerim Jo, and Jae Young Lee. "Polypyrrole-Incorporated Conductive Hyaluronic Acid Hydrogels." Biomaterials research 20, no. 1 (2016): 31.
71. Wang, Weiling, and Ahalapitiya H. Jayatissa. "Comparison Study of Graphene Based Conductive Nanocomposites Using Poly(Methyl Methacrylate) and Polypyrrole as Matrix Materials." Journal of Materials Science: Materials in Electronics 26, no. 10 (2015): 7780-83.
72. Björninen, Miina, Aliisa Siljander, Jani Pelto, Jari Hyttinen, Minna Kellomäki, Susanna Miettinen, Riitta Seppänen, and Suvi Haimi. "Comparison of Chondroitin Sulfate and Hyaluronic Acid Doped Conductive Polypyrrole Films for Adipose Stem Cells." Annals of Biomedical Engineering 42, no. 9 (2014): 1889-900.

73. Bendrea, Anca-Dana, Luminita Cianga, and Ioan Cianga. "Review Paper: Progress in the Field of Conducting Polymers for Tissue Engineering Applications." Journal of Biomaterials Applications 26, no. 1 (2011): 3-84.
74. Thomas, CA, K Zong, P Schottland, and JR Reynolds. "Poly (3, 4-Alkylenedioxypyrrole) S as Highly Stable Aqueous-Compatible Conducting Polymers with Biomedical Implications." Advanced Materials 12, no. 3 (2000): 222-25.
75. Thompson, Brianna C., Simon E. Moulton, Rachael T. Richardson, and Gordon G. Wallace. "Effect of the Dopant Anion in Polypyrrole on Nerve Growth and Release of a Neurotrophic Protein." Biomaterials 32, no. 15 (2011): 3822-31.
76. Chen, Mei-Chin, Yu-Chin Sun, and Yuan-Hsiang Chen. "Electrically Conductive Nanofibers with Highly Oriented Structures and Their Potential Application in Skeletal Muscle Tissue Engineering." Acta Biomaterialia 9, no. 3 (2013): 5562-72.
77. Humpolicek, Petr, Vera Kasparkova, Petr Saha, and Jaroslav Stejskal. "Biocompatibility of Polyaniline." Synthetic Metals 162, no. 7 (2012): 722-27.
78. Guterman, Elizabeth, Shan Cheng, Kolby Palouian, Paul Bidez, Peter Lelkes, and Y Wei. "Peptide-Modified Electroactive Polymers for Tissue Engineering Applications." Paper presented at the ABSTRACTS OF PAPERS OF THE AMERICAN CHEMICAL SOCIETY 2002.
79. Guarino, Vincenzo, Marco Antonio Alvarez-Perez, Anna Borriello, Teresa Napolitano, and Luigi Ambrosio. "Conductive Pani/Pegda Macroporous Hydrogels for Nerve Regeneration." Advanced healthcare materials 2, no. 1 (2013): 218-27.
80. Prabhakaran, M. P., L. Ghasemi-Mobarakeh, G. Jin, and S. Ramakrishna. "Electrospun Conducting Polymer Nanofibers and Electrical Stimulation of Nerve Stem Cells." J Biosci Bioeng 112, no. 5 (2011): 501-7.
81. Abdul Rahman, Norizah, Vaughan Feisst, Michelle E. Dickinson, Jenny Malmström, P. Rod Dunbar, and Jadranka Travas-Sejdic. "Functional Polyaniline Nanofibre Mats for Human Adipose-Derived Stem Cell Proliferation and Adhesion." Materials Chemistry and Physics 138, no. 1 (2013): 333-41.
82. Sista, Prakash, Koushik Ghosh, Jennifer S Martinez, and Reginaldo C Rocha. Polythiophenes in Biological Applications. Vol. 14, 2014.
83. Rad, Armin Tahmasbi, Naushad Ali, Hari Shankar R. Kotturi, Mostafa Yazdimamaghani, Jim Smay, Daryoosh Vashaee, and Lobat Tayebi. "Conducting Scaffolds for Liver Tissue Engineering." Journal of Biomedical Materials Research Part A 102, no. 11 (2014): 4169-81.
84. Karagkiozaki, V, PG Karagiannidis, M Gioti, P Kavatzikidou, D Georgiou, E Georgaraki, and S Logothetidis. "Bioelectronics Meets Nanomedicine for Cardiovascular Implants: Pedot-Based Nanocoatings for Tissue Regeneration." Biochimica et Biophysica Acta (BBA)-General Subjects 1830, no. 9 (2013): 4294-304.
85. Luo, Shyh-Chyang, Emril Mohamed Ali, Natalia C Tansil, Hsiao-hua Yu, Shujun Gao, Eric AB Kantchev, and Jackie Y Ying. "Poly (3, 4-Ethylenedioxythiophene)(Pedot) Nanobiointerfaces: Thin, Ultrasmooth, and Functionalized Pedot Films with in Vitro and in Vivo Biocompatibility." Langmuir 24, no. 15 (2008): 8071-77.
86. Strakosas, Xenofon, Bin Wei, David C Martin, and Roisin M Owens. "Biofunctionalization of Polydioxythiophene Derivatives for Biomedical Applications." Journal of Materials Chemistry B 4, no. 29 (2016): 4952-68.
87. Wang, Gui-Xia, Yong Qian, Xiao-Xiang Cao, and Xing-Hua Xia. "Direct Electrochemistry of Cytochrome C on a Graphene/Poly (3,4-Ethylenedioxythiophene) Nanocomposite Modified Electrode." Electrochemistry communications 20 (2012): 1-3.
88. Groenendaal, Lambertus, Friedrich Jonas, Dieter Freitag, Harald Pielartzik, and John R Reynolds. "Poly (3, 4-Ethylenedioxythiophene) and Its Derivatives: Past, Present, and Future." Advanced Materials 12, no. 7 (2000): 481-94.
89. Spencer, Andrew R., Asel Primbetova, Abigail N. Koppes, Ryan A. Koppes, Hicham Fenniri, and Nasim Annabi. "Electroconductive Gelatin Methacryloyl-Pedot:Pss Composite Hydrogels: Design, Synthesis, and Properties." ACS Biomaterials Science & Engineering 4, no. 5 (2018): 1558-67.
90. Schweizer, Thomas Martin. Electrical Characterization and Investigation of the Piezoresistive Effect of Pedot: Pss Thin Films. Georgia Institute of Technology, 2005.

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

91. Courté, M., M. Alaaeddine, V. Barth, L. Tortech, and D. Fichou. "Structural and Electronic Properties of 2,2′,6,6′-Tetraphenyl-Dipyranylidene and Its Use as a Hole-Collecting Interfacial Layer in Organic Solar Cells." Dyes and Pigments 141 (2017): 487-92.
92. Lee, Gwan-Hyoung, Ryan C. Cooper, Sung Joo An, Sunwoo Lee, Arend van der Zande, Nicholas Petrone, Alexandra G. Hammerberg, Changgu Lee, Bryan Crawford, Warren Oliver, Jeffrey W. Kysar, and James Hone. "High-Strength Chemical-Vapor–Deposited Graphene and Grain Boundaries." Science 340, no. 6136 (2013): 1073-76.
93. Novoselov, K. S., V. I. Fal′ko, L. Colombo, P. R. Gellert, M. G. Schwab, and K. Kim. "A Roadmap for Graphene." Nature 490 (2012): 192.
94. Mayorov, Alexander S., Roman V. Gorbachev, Sergey V. Morozov, Liam Britnell, Rashid Jalil, Leonid A. Ponomarenko, Peter Blake, Kostya S. Novoselov, Kenji Watanabe, Takashi Taniguchi, and A. K. Geim. "Micrometer-Scale Ballistic Transport in Encapsulated Graphene at Room Temperature." Nano Letters 11, no. 6 (2011): 2396-99.
95. Shao, Yuyan, Jun Wang, Hong Wu, Jun Liu, Ilhan A Aksay, and Yuehe Lin. "Graphene Based Electrochemical Sensors and Biosensors: A Review." Electroanalysis 22, no. 10 (2010): 1027-36.
96. Xu, Yuxi, Zhaoyang Lin, Xiaoqing Huang, Yang Wang, Yu Huang, and Xiangfeng Duan. "Functionalized Graphene Hydrogel-Based High-Performance Supercapacitors." Advanced Materials 25, no. 40 (2013): 5779-84.
97. MacHado, B. F., and P. Serp. "Graphene-Based Materials for Catalysis." Catalysis Science and Technology 2, no. 1 (2012): 54-75.
98. Hoa, L. T., J. S. Chung, and S. H. Hur. "A highly Sensitive Enzyme-Free Glucose Sensor Based on Co3o4 Nanoflowers and 3d Graphene Oxide Hydrogel Fabricated Via Hydrothermal Synthesis." Sens. Actuators B (2016): 22376-82.
99. Lee, Wong Cheng, Candy Haley Y. X. Lim, Hui Shi, Lena A. L. Tang, Yu Wang, Chwee Teck Lim, and Kian Ping Loh. "Origin of Enhanced Stem Cell Growth and Differentiation on Graphene and Graphene Oxide." ACS Nano 5, no. 9 (2011): 7334-41.
100. Yang, X., J. Zhu, L. Qiu, and D. Li. "Bioinspired Effective Prevention of Restacking in Multilayered Graphene Films: Towards the Next Generation of High-Performance Supercapacitors." Advanced Materials 23, no. 25 (2011): 2833-38.
101. Loh, Kian Ping, Qiaoliang Bao, Goki Eda, and Manish Chhowalla. "Graphene Oxide as a Chemically Tunable Platform for Optical Applications." Nature Chemistry 2 (2010): 1015.
102. Gao, Wei, Lawrence B Alemany, Lijie Ci, and Pulickel M Ajayan. "New Insights into the Structure and Reduction of Graphite Oxide." Nature Chemistry 1, no. 5 (2009): 403.
103. Liu, Yong, Dingshan Yu, Chao Zeng, Zongcheng Miao, and Liming Dai. "Biocompatible Graphene Oxide-Based Glucose Biosensors." Langmuir 26, no. 9 (2010): 6158-60.
104. Yang, Kai, Hua Gong, Xiaoze Shi, Jianmei Wan, Youjiu Zhang, and Zhuang Liu. "In vivo Biodistribution and Toxicology of Functionalized Nano-Graphene Oxide in Mice after Oral and Intraperitoneal Administration." Biomaterials 34, no. 11 (2013): 2787-95.
105. Zhou, Ming, Yueming Zhai, and Shaojun Dong. "Electrochemical Sensing and Biosensing Platform Based on Chemically Reduced Graphene Oxide." Analytical chemistry 81, no. 14 (2009): 5603-13.
106. Han, Lu, Kezhi Liu, Menghao Wang, Kefeng Wang, Liming Fang, Haiting Chen, Jie Zhou, and Xiong Lu. "Mussel-Inspired Adhesive and Conductive Hydrogel with Long-Lasting Moisture and Extreme Temperature Tolerance." Advanced Functional Materials 28, no. 3 (2018): 1704195.
107. Joung, Young Soo, Robert B. Ramirez, Eric Bailey, Rachel Adenekan, and Cullen R. Buie. "Conductive Hydrogel Films Produced by Freestanding Electrophoretic Deposition and Polymerization at the Interface of Immiscible Liquids." Composites Science and Technology 153 (2017): 128-35.
108. Samanta, Suman K, Asish Pal, Santanu Bhattacharya, and CNR Rao. "Carbon Nanotube Reinforced Supramolecular Gels with Electrically Conducting, Viscoelastic and near-Infrared Sensitive Properties." Journal of Materials Chemistry 20, no. 33 (2010): 6881-90.
109. Esawi, AMK, K Morsi, A Sayed, M Taher, and S Lanka. "Effect of Carbon Nanotube (Cnt) Content on the Mechanical Properties of Cnt-Reinforced Aluminium Composites." Composites Science and Technology 70, no. 16 (2010): 2237-41.

110. Wong, Kenneth Kar Ho, Martin Zinke-Allmang, Jeffery L Hutter, Sabahudin Hrapovic, John HT Luong, and Wankei Wan. "The Effect of Carbon Nanotube Aspect Ratio and Loading on the Elastic Modulus of Electrospun Poly (Vinyl Alcohol)-Carbon Nanotube Hybrid Fibers." Carbon 47, no. 11 (2009): 2571-78.
111. Cellot, Giada, Francesca Maria Toma, Zeynep Kasap Varley, Jummi Laishram, Ambra Villari, Mildred Quintana, Sara Cipollone, Maurizio Prato, and Laura Ballerini. "Carbon Nanotube Scaffolds Tune Synaptic Strength in Cultured Neural Circuits: Novel Frontiers in Nanomaterial–Tissue Interactions." The Journal of Neuroscience 31, no. 36 (2011): 12945-53.
112. Zhang, Faming, Arne Weidmann, J. Barbara Nebe, and Eberhard Burkel. "Osteoblast Cell Response to Surface-Modified Carbon Nanotubes." Materials Science and Engineering: C 32, no. 5 (2012): 1057-61.
113. Shvedova, A. A., V. Castranova, E. R. Kisin, D. Schwegler-Berry, A. R. Murray, V. Z. Gandelsman, A. Maynard, and P. Baron. "Exposure to Carbon Nanotube Material: Assessment of Nanotube Cytotoxicity Using Human Keratinocyte Cells." J Toxicol Environ Health A 66, no. 20 (2003): 1909-26.
114. Yan, Liang, Feng Zhao, Shoujian Li, Zhongbo Hu, and Yuliang Zhao. "Low-Toxic and Safe Nanomaterials by Surface-Chemical Design, Carbon Nanotubes, Fullerenes, Metallofullerenes, and Graphenes." Nanoscale 3, no. 2 (2011): 362-82.
115. Davide, Pantarotto, Singh Ravi, McCarthy David, Erhardt Mathieu, Briand Jean-Paul, Prato Maurizio, Kostarelos Kostas, and Bianco Alberto. "Functionalized Carbon Nanotubes for Plasmid DNA Gene Delivery." Angewandte Chemie International Edition 43, no. 39 (2004): 5242-46.
116. Shim, W., Y. Kwon, S. Y. Jeon, and W. R. Yu. "Optimally Conductive Networks in Randomly Dispersed Cnt:Graphene Hybrids." Sci Rep 5 (2015): 16568.
117. Li, Jing, Chun-yan Liu, and Yun Liu. "Au/Graphene Hydrogel: Synthesis, Characterization and Its Use for Catalytic Reduction of 4-Nitrophenol." Journal of Materials Chemistry 22, no. 17 (2012).
118. Vaitkuviene, Aida, Vilma Ratautaite, Lina Mikoliunaite, Vytautas Kaseta, Giedre Ramanauskaite, Gene Biziuleviciene, Almira Ramanaviciene, and Arunas Ramanavicius. "Some Biocompatibility Aspects of Conducting Polymer Polypyrrole Evaluated with Bone Marrow-Derived Stem Cells." Colloids and Surfaces A: Physicochemical and Engineering Aspects 442 (2014): 152-56.
119. Liu, Xifeng, A. Lee Miller Ii, Sungjo Park, Brian E. Waletzki, Andre Terzic, Michael J. Yaszemski, and Lichun Lu. "Covalent Crosslinking of Graphene Oxide and Carbon Nanotube into Hydrogels Enhances Nerve Cell Responses." Journal of Materials Chemistry B 4, no. 43 (2016): 6930-41.
120. Huyen, Duong. "Carbon Nanotubes and Semiconducting Polymer Nanocomposites." In Carbon Nanotubes-Synthesis, Characterization, Applications: InTech, 2011.
121. Gupta, Namita Dutta, Supratim Maity, and Kalyan Kumar Chattopadhyay. "Field Emission Enhancement of Polypyrrole Due to Band Bending Induced Tunnelling in Polypyrrole-Carbon Nanotubes Nanocomposite." Journal of Industrial and Engineering Chemistry 20, no. 5 (2014): 3208-13.
122. Patton, A. J., L. A. Poole-Warren, and R. A. Green. "Mechanisms for Imparting Conductivity to Nonconductive Polymeric Biomaterials." Macromol Biosci 16, no. 8 (2016): 1103-21.
123. Mietta, José Luis, Pablo I Tamborenea, and R Martin Negri. "Anisotropic Reversible Piezoresistivity in Magnetic–Metallic/Polymer Structured Elastomeric Composites: Modelling and Experiments." Soft Matter 12, no. 2 (2016): 422-31.
124. García, Miguel, Pilar Batalla, and Alberto Escarpa. "Metallic and Polymeric Nanowires for Electrochemical Sensing and Biosensing." TrAC Trends in Analytical Chemistry 57 (2014): 6-22.
125. Gong, Shu, Willem Schwalb, Yongwei Wang, Yi Chen, Yue Tang, Jye Si, Bijan Shirinzadeh, and Wenlong Cheng. "A Wearable and Highly Sensitive Pressure Sensor with Ultrathin Gold Nanowires." Nature communications 5 (2014): 3132.
126. Hsu, Po-Chun, Desheng Kong, Shuang Wang, Haotian Wang, Alex J Welch, Hui Wu, and Yi Cui. "Electrolessly Deposited Electrospun Metal Nanowire Transparent Electrodes." Journal of the American Chemical Society 136, no. 30 (2014): 10593-96.
127. Kim, Areum, Yulim Won, Kyoohee Woo, Chul-Hong Kim, and Jooho Moon. "Highly Transparent Low Resistance Zno/Ag Nanowire/Zno Composite Electrode for Thin Film Solar Cells." ACS Nano 7, no. 2 (2013): 1081-91.
128. Langley, Daniel, Gaël Giusti, Céline Mayousse, Caroline Celle, Daniel Bellet, and Jean-Pierre Simonato. "Flexible Transparent Conductive Materials Based on Silver Nanowire Networks: A Review." Nanotechnology 24, no. 45 (2013): 452001.

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

129. Zhang, Dieqing, Ranran Wang, Meicheng Wen, Ding Weng, Xia Cui, Jing Sun, Hexing Li, and Yunfeng Lu. "Synthesis of Ultralong Copper Nanowires for High-Performance Transparent Electrodes." Journal of the American Chemical Society 134, no. 35 (2012): 14283-86.
130. Lee, Jinhwan, Phillip Lee, Hyungman Lee, Dongjin Lee, Seung Seob Lee, and Seung Hwan Ko. "Very Long Ag Nanowire Synthesis and Its Application in a Highly Transparent, Conductive and Flexible Metal Electrode Touch Panel." Nanoscale 4, no. 20 (2012): 6408-14.
131. Yuan, Tun, Li Zhang, Kuifeng Li, Hongsong Fan, Yujiang Fan, Jie Liang, and Xingdong Zhang. "Collagen Hydrogel as an Immunomodulatory Scaffold in Cartilage Tissue Engineering." Journal of Biomedical Materials Research Part B: Applied Biomaterials 102, no. 2 (2014): 337-44.
132. Lu, Xiaofeng, Wanjin Zhang, Ce Wang, Ten-Chin Wen, and Yen Wei. "One-Dimensional Conducting Polymer Nanocomposites: Synthesis, Properties and Applications." Progress in Polymer Science 36, no. 5 (2011): 671-712.
133. Gouma, P, K Kalyanasundaram, and A Bishop. "Electrospun Single-Crystal Moo 3 Nanowires for Biochemistry Sensing Probes." Journal of materials research 21, no. 11 (2006): 2904-10.
134. Souier, Tewfik, Marco Stefancich, and Matteo Chiesa. "Characterization of Multi-Walled Carbon Nanotube–Polymer Nanocomposites by Scanning Spreading Resistance Microscopy." Nanotechnology 23, no. 40 (2012): 405704.
135. Xiao, Xueliang, Guanzheng Wu, Hongtao Zhou, Kun Qian, and Jinlian Hu. "Preparation and Property Evaluation of Conductive Hydrogel Using Poly (Vinyl Alcohol)/Polyethylene Glycol/Graphene Oxide for Human Electrocardiogram Acquisition." Polymers 9, no. 7 (2017): 259.
136. Zhang, Jianwei, and Dazhi Jiang. "Influence of Geometries of Multi-Walled Carbon Nanotubes on the Pore Structures of Buckypaper." Composites Part A: Applied Science and Manufacturing 43, no. 3 (2012): 469-74.
137. Yang, Junhe, Xia Wang, Xianying Wang, Runping Jia, and Jie Huang. "Preparation of Highly Conductive Cnts/Polyaniline Composites through Plasma Pretreating and in-Situ Polymerization." Journal of Physics and Chemistry of Solids 71, no. 4 (2010): 448-52.
138. Lai, J., L. Zhang, W. Niu, W. Qi, J. Zhao, Z. Liu, W. Zhang, and G. Xu. "One-Pot Synthesis of Gold Nanorods Using Binary Surfactant Systems with Improved Monodispersity, Dimensional Tunability and Plasmon Resonance Scattering Properties." Nanotechnology 25, no. 12 (2014): 125601.
139. Harada, Masafumi, Noriko Tamura, and Mikihito Takenaka. "Nucleation and Growth of Metal Nanoparticles During Photoreduction Using in Situ Time-Resolved Saxs Analysis." The Journal of Physical Chemistry C 115, no. 29 (2011): 14081-92.
140. Dang, Zhi-Min, Jin-Kai Yuan, Jun-Wei Zha, Tao Zhou, Sheng-Tao Li, and Guo-Hua Hu. "Fundamentals, Processes and Applications of High-Permittivity Polymer–Matrix Composites." Progress in Materials Science 57, no. 4 (2012): 660-723.
141. Zhao, Weifeng, Karin Odelius, Ulrica Edlund, Changsheng Zhao, and Ann-Christine Albertsson. "In Situ Synthesis of Magnetic Field-Responsive Hemicellulose Hydrogels for Drug Delivery." Biomacromolecules 16, no. 8 (2015): 2522-28.
142. Ma, Peng-Cheng, Naveed A Siddiqui, Gad Marom, and Jang-Kyo Kim. "Dispersion and Functionalization of Carbon Nanotubes for Polymer-Based Nanocomposites: A Review." Composites Part A: Applied Science and Manufacturing 41, no. 10 (2010): 1345-67.
143. Siddiqui, Naveed A, Erin L Li, Man-Lung Sham, Ben Zhong Tang, Shang Lin Gao, Edith Mäder, and Jang-Kyo Kim. "Tensile Strength of Glass Fibres with Carbon Nanotube–Epoxy Nanocomposite Coating: Effects of Cnt Morphology and Dispersion State." Composites Part A: Applied Science and Manufacturing 41, no. 4 (2010): 539-48.
144. Patton, AJ, RA Green, and LA Poole-Warren. "Mediating Conducting Polymer Growth within Hydrogels by Controlling Nucleation." Apl Materials 3, no. 1 (2015): 014912.
145. Baek, Sungchul, Rylie A Green, and Laura A Poole-Warren. "Effects of Dopants on the Biomechanical Properties of Conducting Polymer Films on Platinum Electrodes." Journal of Biomedical Materials Research Part A 102, no. 8 (2014): 2743-54.
146. Sasaki, Masato, Bijoy Chandapillai Karikkineth, Kuniaki Nagamine, Hirokazu Kaji, Keiichi Torimitsu, and Matsuhiko Nishizawa. "Highly Conductive Stretchable and Biocompatible Electrode–Hydrogel Hybrids for Advanced Tissue Engineering." Advanced healthcare materials 3, no. 11 (2014): 1919-27.

147. Otero, TF, I Boyano, MT Cortes, and G Vazquez. "Nucleation, Non-Stoiquiometry and Sensing Muscles from Conducting Polymers." Electrochimica Acta 49, no. 22-23 (2004): 3719-26.
148. Kim, Yong Seok, Kanghee Cho, Hyun Jong Lee, Sooho Chang, Hyungsuk Lee, Jung Hyun Kim, and Won-Gun Koh. "Highly Conductive and Hydrated Peg-Based Hydrogels for the Potential Application of a Tissue Engineering Scaffold." Reactive and Functional Polymers 109 (2016): 15-22.
149. Liu, Jun, B Reeja-Jayan, and Arumugam Manthiram. "Conductive Surface Modification with Aluminum of High Capacity Layered Li [Li0. 2mn0. 54ni0. 13co0. 13] O2 Cathodes." The Journal of Physical Chemistry C 114, no. 20 (2010): 9528-33.
150. Xie, J., M. R. Macewan, S. M. Willerth, X. Li, D. W. Moran, S. E. Sakiyama-Elbert, and Y. Xia. "Conductive Core-Sheath Nanofibers and Their Potential Application in Neural Tissue Engineering." Adv Funct Mater 19, no. 14 (2009): 2312-18.
151. Kurniawan, D, FM Nor, HY Lee, and JY Lim. "Elastic Properties of Polycaprolactone at Small Strains Are Significantly Affected by Strain Rate and Temperature." Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 225, no. 10 (2011): 1015-20.
152. Annabi, Nasim, Su Ryon Shin, Ali Tamayol, Mario Miscuglio, Mohsen Afshar Bakooshli, Alexander Assmann, Pooria Mostafalu, Jeong-Yun Sun, Suzanne Mithieux, Louis Cheung, Xiaowu Tang, Anthony S. Weiss, and Ali Khademhosseini. "Highly Elastic and Conductive Human-Based Protein Hybrid Hydrogels." Advanced Materials 28, no. 1 (2016): 40-49.
153. Luo, Xiliang, and Xinyan Tracy Cui. "Sponge-Like Nanostructured Conducting Polymers for Electrically Controlled Drug Release." Electrochemistry communications 11, no. 10 (2009): 1956-59.
154. Wang, Huiqiang, Hongliang Han, and Zhanfang Ma. "Conductive Hydrogel Composed of 1, 3, 5-Benzenetricarboxylic Acid and Fe3+ Used as Enhanced Electrochemical Immunosensing Substrate for Tumor Biomarker." Bioelectrochemistry 114 (2017): 48-53.
155. Yang, B., F. Yao, T. Hao, W. Fang, L. Ye, Y. Zhang, Y. Wang, J. Li, and C. Wang. "Development of Electrically Conductive Double-Network Hydrogels Via One-Step Facile Strategy for Cardiac Tissue Engineering." Adv Healthc Mater 5, no. 4 (2016): 474-88.
156. Gajendiran, Mani, Jonghoon Choi, Se-Jeong Kim, Keongsoo Kim, Heungsoo Shin, Hyung-Jun Koo, and Kyobum Kim. "Conductive Biomaterials for Tissue Engineering Applications." Journal of Industrial and Engineering Chemistry 51 (2017): 12-26.
157. Qazi, Taimoor H., Ranjana Rai, Dirk Dippold, Judith E. Roether, Dirk W. Schubert, Elisabetta Rosellini, Niccoletta Barbani, and Aldo R. Boccaccini. "Development and Characterization of Novel Electrically Conductive Pani–Pgs Composites for Cardiac Tissue Engineering Applications." Acta Biomaterialia 10, no. 6 (2014): 2434-45.
158. Hosseinzadeh, Simzar, Sayed Mahdi Rezayat, Ebrahim Vashegani-Farahani, Matin Mahmoudifard, Soheila Zamanlui, and Masoud Soleimani. "Nanofibrous Hydrogel with Stable Electrical Conductivity for Biological Applications." Polymer 97 (2016): 205-16.
159. Jo, H., M. Sim, S. Kim, S. Yang, Y. Yoo, J. H. Park, T. H. Yoon, M. G. Kim, and J. Y. Lee. "Electrically Conductive Graphene/Polyacrylamide Hydrogels Produced by Mild Chemical Reduction for Enhanced Myoblast Growth and Differentiation." Acta Biomater 48 (2017): 100-09.
160. Ahadian, S., R. Banan Sadeghian, S. Yaginuma, J. Ramon-Azcon, Y. Nashimoto, X. Liang, H. Bae, K. Nakajima, H. Shiku, T. Matsue, K. S. Nakayama, and A. Khademhosseini. "Hydrogels Containing Metallic Glass Sub-Micron Wires for Regulating Skeletal Muscle Cell Behaviour." Biomater Sci 3, no. 11 (2015): 1449-58.
161. Navaei, A., H. Saini, W. Christenson, R. T. Sullivan, R. Ros, and M. Nikkhah. "Gold Nanorod-Incorporated Gelatin-Based Conductive Hydrogels for Engineering Cardiac Tissue Constructs." Acta Biomater 41 (2016): 133-46.
162. Ahadian, S., S. Yamada, J. Ramon-Azcon, M. Estili, X. Liang, K. Nakajima, H. Shiku, A. Khademhosseini, and T. Matsue. "Hybrid Hydrogel-Aligned Carbon Nanotube Scaffolds to Enhance Cardiac Differentiation of Embryoid Bodies." Acta Biomater 31 (2016): 134-43.
163. Kharaziha, Mahshid, Su Ryon Shin, Mehdi Nikkhah, Seda Nur Topkaya, Nafiseh Masoumi, Nasim Annabi, Mehmet R. Dokmeci, and Ali Khademhosseini. "Tough and Flexible Cnt–Polymeric Hybrid Scaffolds for Engineering Cardiac Constructs." Biomaterials 35, no. 26 (2014): 7346-54.

Peer-reviewed version available at Polymers 2018, 10, 1078; doi:10.3390/polym10101078

164. Shin, Su Ryon, Sung Mi Jung, Momen Zalabany, Keekyoung Kim, Pinar Zorlutuna, Sang bok Kim, Mehdi Nikkhah, Masoud Khabiry, Mohamed Azize, and Jing Kong. "Carbon-Nanotube-Embedded Hydrogel Sheets for Engineering Cardiac Constructs and Bioactuators." ACS Nano 7, no. 3 (2013): 2369-80.
165. Shi, Z., H. Gao, J. Feng, B. Ding, X. Cao, S. Kuga, Y. Wang, L. Zhang, and J. Cai. "In Situ Synthesis of Robust Conductive Cellulose/Polypyrrole Composite Aerogels and Their Potential Application in Nerve Regeneration." Angew Chem Int Ed Engl 53, no. 21 (2014): 5380-4.
166. Bu, Ying, Hai-Xing Xu, Xin Li, Wen-Jin Xu, Yi-xia Yin, Hong-lian Dai, Xiao-bin Wang, Zhi-Jun Huang, and Pei-Hu Xu. "A Conductive Sodium Alginate and Carboxymethyl Chitosan Hydrogel Doped with Polypyrrole for Peripheral Nerve Regeneration." RSC Advances 8, no. 20 (2018): 10806-17.
167. Sumi, Yang, Jang LindyK., Kim Semin, Yang Jongcheol, Yang Kisuk, Cho Seung-Woo, and Lee Jae Young. "Polypyrrole/Alginate Hybrid Hydrogels: Electrically Conductive and Soft Biomaterials for Human Mesenchymal Stem Cell Culture and Potential Neural Tissue Engineering Applications." Macromolecular Bioscience 16, no. 11 (2016): 1653-61.
168. Xu, Haixing, Jeremy M. Holzwarth, Yuhua Yan, Peihu Xu, Hua Zheng, Yixia Yin, Shipu Li, and Peter X. Ma. "Conductive Ppy/Pdlla Conduit for Peripheral Nerve Regeneration." Biomaterials 35, no. 1 (2014): 225-35.
169. Liu, Xifeng, A. Lee Miller, Sungjo Park, Brian E. Waletzki, Zifei Zhou, Andre Terzic, and Lichun Lu. "Functionalized Carbon Nanotube and Graphene Oxide Embedded Electrically Conductive Hydrogel Synergistically Stimulates Nerve Cell Differentiation." ACS Applied Materials & Interfaces 9, no. 17 (2017): 14677-90.
170. Javadi, M., Q. Gu, S. Naficy, S. Farajikhah, J. M. Crook, G. G. Wallace, S. Beirne, and S. E. Moulton. "Conductive Tough Hydrogel for Bioapplications." Macromol Biosci 18, no. 2 (2018).
171. Bose, Susmita, Mangal Roy, and Amit Bandyopadhyay. "Recent Advances in Bone Tissue Engineering Scaffolds." Trends in biotechnology 30, no. 10 (2012): 546-54.
172. Demirtaş, Tuğrul Tolga, Gülseren Irmak, and Menemşe Gümüşderelioğlu. "A Bioprintable Form of Chitosan Hydrogel for Bone Tissue Engineering." Biofabrication 9, no. 3 (2017): 035003.
173. Liu, DanDan, JinChao Zhang, ChangQing Yi, and MengSu Yang. "The Effects of Gold Nanoparticles on the Proliferation, Differentiation, and Mineralization Function of Mc3t3-E1 Cells in Vitro." Chinese science bulletin 55, no. 11 (2010): 1013-19.
174. Heo, Dong Nyoung, Wan-Kyu Ko, Min Soo Bae, Jung Bok Lee, Deok-Won Lee, Wook Byun, Chang Hoon Lee, Eun-Cheol Kim, Bock-Young Jung, and Il Keun Kwon. "Enhanced Bone Regeneration with a Gold Nanoparticle–Hydrogel Complex." J. Mater. Chem. B 2, no. 11 (2014): 1584-93.
175. Khorshidi, S., and A. Karkhaneh. "Hydrogel/Fiber Conductive Scaffold for Bone Tissue Engineering." J Biomed Mater Res A 106, no. 3 (2018): 718-24.
176. Zanjanizadeh Ezazi, N., M. A. Shahbazi, Y. V. Shatalin, E. Nadal, E. Makila, J. Salonen, M. Kemell, A. Correia, J. Hirvonen, and H. A. Santos. "Conductive Vancomycin-Loaded Mesoporous Silica Polypyrrole-Based Scaffolds for Bone Regeneration." Int J Pharm 536, no. 1 (2018): 241-50.
177. Pelto, J., M. Bjorninen, A. Palli, E. Talvitie, J. Hyttinen, B. Mannerstrom, R. Suuronen Seppanen, M. Kellomaki, S. Miettinen, and S. Haimi. "Novel Polypyrrole-Coated Polylactide Scaffolds Enhance Adipose Stem Cell Proliferation and Early Osteogenic Differentiation." Tissue Eng Part A 19, no. 7-8 (2013): 882-92.
178. Lu, J., C. Cheng, Y. S. He, C. Lyu, Y. Wang, J. Yu, L. Qiu, D. Zou, and D. Li. "Multilayered Graphene Hydrogel Membranes for Guided Bone Regeneration." Adv Mater 28, no. 21 (2016): 4025-31.
179. Chen, J., M. Yu, B. Guo, P. X. Ma, and Z. Yin. "Conductive Nanofibrous Composite Scaffolds Based on in-Situ Formed Polyaniline Nanoparticle and Polylactide for Bone Regeneration." J Colloid Interface Sci 514 (2018): 517-27.