Injectable Graphene Oxide/Hydrogel-Based Angiogenic Gene Delivery System for Vasculogenesis and Cardiac Repair

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ABSTRACT
The objective of this study was to develop an injectable and biocompatible hydrogel which can efficiently deliver a nanocomplex of graphene oxide (GO) and vascular endothelial growth factor-165 (VEGF) pro-angiogenic gene for myocardial therapy. For the study, an efficient nonviral gene delivery system using polyethylenimine (PEI) functionalized GO nanosheets (fGO) complexed with DNA<sub>VEGF</sub> was formulated and incorporated in the low-modulus methacrylated gelatin (GelMA) hydrogel to promote controlled and localized gene therapy. It was hypothesized that the fGO<sub>VEGF</sub>/GelMA nanocomposite hydrogels can efficiently transfect myocardial tissues and induce favorable therapeutic effects without invoking cytotoxic effects. To evaluate this hypothesis, a rat model with acute myocardial infarction was used, and the therapeutic hydrogels were injected intramyocardially in the peri-infarct regions. The secreted VEGF from in vitro transfected cardiomyocytes demonstrated profound mitotic activities on endothelial cells. A significant increase in myocardial capillary density at the injected peri-infarct region and reduction in scar area were noted in the infarcted hearts with fGO<sub>VEGF</sub>/GelMA treatment compared to infarcted hearts treated with untreated sham, GelMA and DNA<sub>VEGF</sub>/GelMA groups. Furthermore, the fGO<sub>VEGF</sub>/GelMA group showed significantly higher (<i>p < 0.05, n = 7</i>) cardiac performance in echocardiography compared to other groups, 14 days postinjection. In addition, no significant differences were noticed between GO/GelMA and non-GO groups in the serum cytokine levels and quantitative PCR based inflammatory microRNA (miRNA) marker expressions at the injected sites. Collectively, the current findings suggest the feasibility of a combined hydrogel-based gene therapy system for ischemic heart diseases using nonviral hybrid complex of fGO and DNA.

KEYWORDS: nanomedicine · graphene oxide · injectable hydrogel · gene delivery · myocardial therapy

Hydrogels have played an increasingly important role in tissue engineering. This is mainly attributed to the unique properties of hydrogels including their high permeability, biodegradability, tunable physical properties, ability to provide structural support to bioengineered tissue constructs, as well as to surface coat medical implants for improved biocompatibility. Hydrogels can also be made biofunctional by tethering suitable growth factors, therapeutic peptides or drugs molecules for specific tissue-type applications. However, these approaches are limited by short half-life, low binding efficiency of the drugs or peptides, and inability to induce long-term therapeutic effects. Hydrogels have also been used as a platform to support viral, nonviral and nanoparticle-based gene delivery systems. Encapsulating such gene delivery vectors inside hydrogels enables their controlled delivery.
delivery at the desired site, preventing unwanted loss during the transit to the target site and allowing efficient localized gene therapy with reduced nonspecific spreading to other tissues. Thus, the hydrogel increases the local retention time of the vector at the target site, enhancing their chances of getting internalized by the tissues, which is currently a major limitation of nonviral nanoparticle-based delivery systems. For example, it has been reported that alginate hydrogels, containing DNA–PEI aggregates, can enhance DNA uptake depending on the stiffness of the gel.

Hydrogel/nanoparticle-based gene delivery system can be used to develop advanced bioactive hydrogels with tissue-specific functionalities. Such a system can efficiently deliver biotherapeutic molecules in a controlled and localized manner, as well as it can utilize the cell's own machinery for continuous and sustained production of the therapeutic protein, which is not possible with bulk protein delivery methods. Studies so far have shown that mammalian viral gene delivery vectors, in combination with hydrogels, can be used for gene delivery applications. However, nonviral vectors are clinically more attractive because of their advantageous features including superior biosafety profile, reduced risk of adverse immune reaction and negligible chance of viral gene integration to the host genome thereby zero risk of insertional mutagenesis. A major disadvantage of nonviral nanoparticles compared to viral systems is poor transfection efficiency. It has been recently reported that graphene oxide (GO) nanosheets, a precursor of graphene, can be efficiently used to deliver genes efficiently when ionically bonded to cationic polymers such as PEI. PEI is known as a suitable material for gene transfer because it binds strongly to DNA, demonstrates proton sponge effects, and helps in escape of the delivered nucleic acids from endosomal/lysosomal pathways after cell internalization. Low molecular weight branched PEI is also known to have low cytotoxicity and can significantly enhance gene delivery efficiency in combination with GO. This is mainly because of its unique delivery features such as suitable water dispersibility, high surface area and aspect ratio, efficient biomolecule loading and effective cell internalization properties.

In this regard, understanding the therapeutic potential of a hydrogel-based GO gene delivery system approach will be beneficial for enabling a range of therapeutic applications.

In this study, we have developed a low-modulus GelMA hydrogel, which is a chemically modified form of native gelatin protein. It was selected because of its biocompatibility, biodegradability and ability to support the formation of microvasculature and endothelial cord formation in vitro and in vivo. This modified form of denatured collagen has the unique advantages of both natural and synthetic biomaterials. It retains the natural RGD-motifs of collagen that mediate cell attachment, while at the same time preserves the matrix degradation sites. Additionally, conjugation of gelatin with methacrylate groups helps to form photo-polymerizable hydrogels with tunable mechanical and degradation properties. GelMA is also nontoxic to the cells when used under the optimal concentrations and degrees of methacrylation as reported in our earlier studies. It has been previously demonstrated that GelMA can be microengineered to fabricate organized vasculature in vitro, support microvascular networks in vivo and support cardiomyocytes in a three-dimensional (3D) microenvironment when blended with carbon-based nanoparticles such as multiwalled carbon nanotubes (CNTs) and GO to generate mechanically strong, electroconductive hydrogels. Here, GelMA has been impregnated with fGO nanosheets, for site-specific gene delivery of pro-angiogenic human vascular endothelial growth factor plasmid DNA (pDNAVEGF) to damaged cardiac tissues. This injectable GelMA hydrogel (GG), carrying fGOVEGF (pDNAVEGF bound to fGO), was expected to induce a combinatorial effect, which would facilitate local myocardial neovascularisation at the injected sites, reduce fibrosis and potentially improve cardiac function in an in vivo model of acute myocardial infarction (AMI). Figure 1a illustrates the overall process of in vitro preparation of GelMA/fGO hydrogel-based hybrid gene delivery system and its in vivo localized administration in the heart for prolonged gene expression and therapy. The injectable GelMA matrix system would not only facilitate sustained supply of angiogenic genes to the myocardial tissues, but also provide protection of entrapped DNA against external harsh environment in the beating heart.

RESULTS AND DISCUSSION

Rheological Properties of the Formulated Hydrogel. To use the GO/GelMA nanocomposite hydrogels as an injectable gene delivery agent, the hydrogel should pass through surgical needles with minimum efforts. Moreover, after injection, the hydrogel should regain its mechanical properties and structural stability. To achieve such a clinically relevant material and facilitate easy release of fGOVEGF nanosheets, here we used low degree methacrylation GelMA whose injectability properties were evaluated by viscosity studies using rheometer and mechanical property analyzer. The preliminary investigation using a 22-gauge needle indicates that all the nanocomposite hydrogel compositions can be easily injected (Figure 1b (inset)). For minimally invasive therapies, the hydrogels should be easily injected near the wound site and should have sufficient mechanical strength to withstand in vivo stresses. The ability of fGO/GelMA nanocomposites to flow under mechanical stress was determined by evaluating the shear thinning capability. In this, a
constant shear rate was applied to the hydrogel, and the viscosity was monitored. The decrease in the viscosity with increasing shear rate indicated that the nanocomposite hydrogels start flowing under mechanical stress. The results indicate that GelMA readily flows and the mechanical integrity is totally lost as the viscosity of GelMA was ~1 Pa.s at the shear rate of 50 s⁻¹ (Figure 1b). The addition of fGO significantly increased the viscosity of the nanocomposite hydrogels at higher strain rate. This is mainly attributed to the physical interaction of surface functionalized fGO nanosheets, with GelMA. Moreover, with the addition of fGO to GelMA, mechanical strength of the hydrogel network was enhanced. This was also evident from the increase in storage modulus (G') and loss modulus (G'') of fGO/GelMA network in stress sweep, strain sweep and frequency sweep experiments compared to GelMA hydrogels (Figure S1). Overall, fGO/GelMA hydrogels were easily injectable using surgical needle, and the addition of fGO significantly reinforces the physical network of the nanocomposite hydrogels.

Characterization of the fGO/DNA Nanocomplex. Our main hypothesis was that an injectable hydrogel that induces localized gene therapy can significantly improve myocardial tissue repairing mechanisms. Recent works in small and large experimental animals have demonstrated that injectable hydrogels, comprising mainly native extracellular matrix (ECM), peptide-bound biopolymers, or myocardial ECM derived materials, can be effective in cardiac repair after infarction.\textsuperscript{34-40} This is
because these hydrogels provide cardiac specific structural support, stimulate local healing mechanism, and generate bioactive products in the tissue microenvironment to promote endogenous stem cell homing. For instance, Iffkovits et al. demonstrated that mechanically tunable methacrylated hyaluronic acid hydrogels could be used as an injectable therapeutic biomaterial for healing of cardiac damage.40 Similarly, it was postulated that the injectable GelMA hydrogel, comprised of natural biochemical cues, will be beneficial to the ischemic tissue that will potentially support vascular cell infiltration and endogenous repair mechanisms.

An important criterion while formulating an efficient gene delivery system is to establish a strong binding of negatively charged DNA to the surfaces of dispersed cationic fGO nanosheets. This was verified by transmission electron microscopy (TEM) confirming uniform nanostructure formation with good dispersivity, and zeta potential analysis confirming successful binding of fGO to pDNA (Figure 1a and Figure S2) following protocol mentioned elsewhere.18 The TEM micrographs gave morphological evidence that the untreated GO (∼5 μm) formed homogeneously dispersed nanocomplexes of DNA phosphates. N/P ratio of 16, represented as fGO, showed a highly positive charge (43.0 ± 3.2 mV). On the other hand, fGO showed a highly positive charge (43.0 ± 3.2 mV). The positive zeta potential value of fGO, upon binding with the negatively charged pDNA, was reduced. The resulting zeta potential values depended on the N/P ratios, where N/P stands for the ratio of moles of the amine groups of cationic PEI polymer to those of the DNA phosphates. N/P ratio of 16, represented as fGO (16), showed highest zeta potential (15.8 ± 3.5 mV), while at N/P ratio of 4 the charge decreased to negative value because of overloaded pDNA on fGO surfaces. This result confirmed the efficient hybrid complex formation, generated by strong electrostatic interactions of plasmid DNA with fGO nanosheets under optimized condition as reported elsewhere.18 The MTS tetrazolium cytotoxicity assay (Promega, Madison, WI) of fGO nanocomplexes with embryonic rat cardiomyocytes (H9c2 cells, ATCC) confirmed that fGO (N/P ratios ranging from 4 to 16) did not invoke statistically significant cytotoxic effects on the H9c2 cells compared to untreated control (Figure S3).

**In Vitro Gene Delivery of the Hydrogel.** To prepare the gene delivery system, fGOVEGF was dispersed by vortexing in 5% GelMA prepolymer solution and the prepolymer mixture was photo-cross-linked under optimized UV exposure based on previously established protocol, to form low modulus injectable hydrogel.31 To confirm the release of fGOVEGF nanocomplexes from the hydrogel, the latter was incubated in phosphate buffer saline (PBS) solution for 72 h and samples were collected in regular intervals for agarose gel electrophoretic run (Figure S4A). The detected band intensities for different time points in the gel confirm slow release of pDNA from GelMA over 72 h, while the retention of these bands within the wells of the agarose gel confirms that pDNA was still bound to the fGO that led to the retardation of electromobility shift of the bound pDNA, similar to other studies.18,21 This was followed by transfection of the cardiomyocytes with the eluted fGO_{GFP}, carrying green fluorescent protein (GFP) gene, or fGO_{VEGF} nanocomplexes from the GelMA hydrogels, where fGO (16)_{GFP} showed highest transfection efficiency (Figure S4B). The release profile of VEGF protein in conditioned media (CM) from fGO (16)_{VEGF} transfected H9c2 cardiomyocytes showed rapid overexpression of the growth factor in the first 4 days post-transfection as quantified by ELISA, while it gradually decreased over time by day 14 (Figure S4C). The data also reconfirmed that GG group can significantly enhance the gene delivery efficiency compared to GG (GelMA with free pDNA_{VEGF}) and control G (only GelMA) groups.

**In Vitro Pro-Angiogenic Activities of the Hydrogel.** The bioactivities of the released VEGF by GG group were evaluated in vitro by investigating the proliferative capacity of the human umbilical vein endothelial cells (HUVECs) in 3D culture in high degree methacrylated (∼80%) GelMA hydrogel. MTS assay was used to assess the proliferation potential of HUVECs treated with CM (containing VEGF secreted by H9c2) from experimental samples.41 The results were illustrated as percent increase in HUVEC proliferation relative to that induced by CM from unstimulated control group (taken as 100%). As shown in Figure 2a (i), CM from group GG showed highest HUVEC proliferation (133.9 ± 6.0%) compared to GG + Ab and Control (Nontreated) groups. This is because the overexpressed VEGF from H9c2 cardiomyocytes was neutralized with antibodies in GG + Ab group. This proliferation rate was directly dependent on the amount of the VEGF released which explains why the treated group demonstrated better results than nontreated Control and GG + Ab groups. The lower left panel in Figure 2a (ii) represents the calcein stained HUVECs in 3D hydrogel in different groups. Interestingly, the GG group also showed sprouting of HUVECs in the hydrogel which was absent in other groups. Furthermore, we tested the ability of CMs from different groups to increase HUVEC wound healing in a 2D monolayer as demonstrated in other studies.42 As depicted in Figure 2b (i) and the corresponding representative pictures in lower right panel in Figure 2b (ii), stimulation of wounded HUVEC monolayer with CM from GG induced significant healing of wound area (25.6 ± 3.1%) compared to CM from unstimulated control (5.4 ± 0.7%) and GG + Ab group (2.5 ± 0.1%). Preincubation of CM with the neutralizing anti-VEGF antibodies completely hindered VEGF
induced wound healing, clearly suggesting that chemotactic signals from VEGF enhances the wound healing effect. In addition, we explored whether CM can also induce HUVEC attachment and spreading in a hydrogel-based channel system within restricted microenvironment. As described in earlier studies, a microchannel was formed inside GelMA hydrogel (high degree methacrylate) and 5 × 10^6 HUVECs/mL

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**Figure 2.** *In vitro* functionalities of GG’ hydrogel on HUVECs. (a i and ii) Proliferation of HUVECs in 3D, grown in the presence of conditioned media (CM, without or with excess of neutralizing anti-VEGF antibodies, Ab: 1 mg/mL) from fGO/DNA/VEGF/GelMA transfected H9c2 cardiomyocytes. As control group, CM from nontreated cells was taken. A total of 50 μL of GelMA prepolymer containing HUVECs were added per well in 96 well-plate. After photo-cross-linking was performed, the cell containing gels were grown in different CMs for 96 h. Cell proliferations were detected by MTS colorimetric assay, while data (n = 3) presented in graph were normalized by that from control group. Lower left panel shows the representative photomicrographs of each group where HUVECs were stained with calcein dye. Interestingly, HUVEC in GG’ group, apart from inducing significant proliferation, also demonstrated highly branched tube-like structure formation absent in other groups. (b i and ii) VEGF-induced migration of HUVECs in wound healing scratch assay. HUVEC monolayer was wounded with cell scraper and treated with CM from different groups. HUVECs were photographed 12 h post-treatment (lower panel) and the percentage of scratched area (which was initially free of cells, marked by the white dotted border lines) covered by the migrated cells were analyzed using ImageJ software. (c i–iii) To confirm the potential of CM in combination with GelMA biomaterial to produce vascularized microstructures, HUVEC adhesion and migration assay inside GelMA (highly methacrylated) microchannels was performed. The microchannel was made by needle (200 μm) insertions and photo-cross-linking. In all groups, HUVECs were suspended in CM from individual groups and seeded inside the microchannel. After 24 h, photomicrographs of the cell cultured microchannels (lower panel) were taken and analyzed for percentage of microchannel area covered by adhered and migrated HUVECs in different experimental groups. Data are expressed as mean value ± standard deviation (SD). ***P < 0.001, n = 3. Scale bar: 100 μm.
was grown inside the microchannel in the presence of CM from different groups. Twenty-four hours post incubation with CM from different groups demonstrate that GG group had significantly higher HUVEC attachment and spreading inside the microchannel compared to GG (Figure 2c: 58.5 ± 9.1% vs 26.4 ± 6.4%). These data confirmed the proliferative, wound healing and chemotactic effects of VEGF, secreted from GG, transfected H9c2 cells.

**In Vivo Biocompatibility of fGO/GelMA Hydrogel.** Despite the multiple clinical trials and growing understanding in cardiovascular research, clinical outcomes of currently available AMI treatments are deeply influenced by the post AMI complications, such as inflammation, stent thrombosis, and other life threatening cardiovascular risk factors. However, promoting vascularization at the injured site to reduce scar formation and ventricular remodeling has been considered as a viable treatment method, as observed in several gene therapy studies with viral vectors. Taking advantage of the complementary strengths of GO, such as relatively high therapeutics loading capacity, low immunogenicity and high gene delivery efficiency, along with microvascular network supporting properties of biodegradable GelMA hydrogel, here we developed fGOVEGF carrying injectable GelMA hydrogel and hypothesized that it will be able to successfully treat AMI in vivo.

As establishing the in vivo biocompatibility of the formulated GO-based hydrogel is of paramount importance, building on the in vitro results, here we investigated its inflammatory effects in immunocompetent rat model with AMI. The AMI was induced in the rat models by occlusion of the left anterior descending coronary artery according to established laboratory procedures. Subsequently, 300 μL of injectable hybrid hydrogels was intramyocardially injected at three different sites in the peri-infarct regions of the heart (Figure 3a). One group received fGO suspended in 5% GelMA hydrogel (G, n = 3) and the control sham group received only similar infarction (G, n = 3). Seven days post injection, the formalin fixed paraffin embedded tissue sections, specifically from the injected regions, were isolated using laser capture microscope (LCM). This was followed by total RNA extraction for quantitative analysis of four different miRNAs, and detection of the changes in inflammatory marker expression compared to untreated control. The miRNAs are small, noncoding RNA molecules (~20 nucleotides) present in introns and exons of noncoding transcripts and can influence transcriptional regulators, cytokines and cell surface receptors, thereby affecting the entire inflammation and immune response system. The markers chosen for the study include miRNAs for proinflammatory role (miR-155), inflammation resolution role (miR-146a), cardiac aging and function (miR-34a) and cardioprotective role under apoptotic condition (miR-145). Quantitative PCR (qPCR) analysis showed no significant differences between control and tested animals for all the four miRNAs analyzed in the study (Figure 3b). Similar results were obtained by ELISA analysis of pro-inflammatory tumor necrosis factor α (TNFa) and anti-inflammatory interleukin-10 (IL10) cytokines in blood plasma where no significant differences were detected in the ratio of pro/anti-inflammatory cytokines between fGO/GelMA and control group (Figure 3c). Similar observations were reported in a recent study by Chowdhury et al. where the group used dextran functionalized graphene nanoplatelets to assess the hematological and inflammatory responses in vivo. Concomitantly, this trend was noticed by immunostaining myocardial tissue sections for TNFa expression (Figure 3d) and hematoxylin and eosin (H&E) staining (Figure 3e) to assess acute inflammatory cell infiltration to the inflammatory site. These data confirmed that the combination of GO and GelMA did not invoke any significant toxicity or inflammatory response in vivo.

**In Vivo Therapeutic Efficacy in Myocardially Infarcted Rat Model.** After confirming in vivo biocompatibility, we evaluated the in vivo therapeutic efficacy of the fGOVEGF based hydrogel in rat model with AMI using established analysis methods. At first, the gene delivery efficiency was confirmed by fGO LacZ/ GelMA (Figure 4a), where Lac Z was used as the β-galactosidase coding reporter gene to trace the protein expression in the transfected heart tissue. This was confirmed 7 days post operation, by the localized 5-bromo-4-chloro-3-indolyl-β-D-galacto-pyranoside (X-gal) staining of the myocardial tissue at the injected sites (Figure 4b,c). The analysis of the X-gal-stained heart revealed that the LacZ gene expression was mainly limited to the injected regions surrounding the infarct region as indicated by the blue X-gal staining. In a similar way, to achieve highly localized transfection and angiogenic effects in myocardial tissue, injectable GelMA carrying fGOVEGF hydrogels were administered via direct intramyocardial injections at the peri-infarct region post infarction. It was postulated that the strong angiogenic effect of the hydrogel would help in promoting vasculogenesis, reducing scar area formation and improving the heart function in treatment groups. Toward this goal, a total of 28 immunocompetent rats were used for in vivo efficacy experiment (Groups: GG = fGOVEGF/GelMA; GG = DNAVEGF/GelMA; G = GelMA, control = nontreated; n=7). The neovascularization formation in the peri-infarct area was assessed by detecting the capillary (Figure 4d) and artery densities...
(Figure 4e). For this, immunohistochemical staining was performed with antibodies against (platelet endothelial cell adhesion molecule-1) PECAM-1 for identification of HUVECs and smooth muscle α-actin for tracing the smooth muscle cells. As shown in Figure 4d, significant improvements were observed in capillary density in the GG0 compared to other groups (148.7 ± 21.2/mm² for GG0, 115.6 ± 8.4/mm² for GG vs 118.0 ± 17.4/mm² for G, 94.5 ± 15.2 for untreated control, p < 0.001) analyzed by immunostaining against PECAM endothelial marker (Figure S5A). This indicates that the treatment group was able to induce neoangiogenesis in a paracrine way by releasing VEGF angiogenic factors to stimulate localized vessel sprouting through improved paracrine VEGF secretion. However, no significant differences in arteriole densities (p > 0.05) were found between the groups as reported in Figure 4e and Figure S5B with smooth muscle α-actin staining. Histomorphometric analysis of sirius red stained heart sections confirmed that the treatment helped to attenuate scar area formation (Figure S5A, b: 19.4 ± 5.8% for GG0, 28.1 ± 4.2% for GG vs 27.5 ± 7.7% for G, 35.6 ± 4.2% for control, p < 0.01). This data is in support of earlier studies, which showed that increment in blood vessel density could support reduction of scar formation.42,46,47 GG0 group also significantly reduced the fibrotic area compared to GG as observed from ventricular infarct area analysis. To investigate if the reduction in scar formation improved heart function, the cardiac ejection fraction percentage (EF%) at
different time periods (day 3 and 14) were monitored using echocardiography.\textsuperscript{42,46} EF\% of all of the groups was around 30\% (baseline) on day 3 post infarction, indicating successful AMI in all groups. As presented in Figure 5c, significant improvement was observed in EF\% of GG\' group compared to other experimental groups by day 14 (49.4 ± 3.8\% for GG\' vs 41.8 ± 4.2\% for GG vs 38.4 ± 6.4\% for G vs 36.4 ± 5.6\% for control, p < 0.01).
CONCLUSIONS

In summary, this new gene-activated hybrid material promises new advancement in AMI therapy to meet the current clinical needs. The study not only confirms the in vivo efficacy of the developed hydrogel for post-AMI therapy but also provides insights into the biocompatibility aspects of the system. This strategy is particularly advantageous compared to widely studied stem cell therapy whose application is limited mostly by frequent immune rejections by patients, maintenance of cell viability and retention at the target site, chances of teratoma formation, along with plethora of ethical, logistical and technical challenges for cell isolation and culturing. Moreover the fGO-based hydrogel was characterized by scanning electron microscopy, rheological property testing and zeta-potential analysis. These tests confirmed suitable injectability and DNA adhesion properties of the fGO-based hydrogel formulation. Collectively, the study underscores the utility of this hydrogel-based, nonviral gene delivery system which can effectively transfer genes in vivo as well as induce sustained therapeutic effects. The formulation is simple and can be easily applied to plasmid DNA and other nucleic acid delivery systems for site-specific treatment of different diseases. The strategy can also limit the number of doses necessary for long-term effects, compared to the bolus doses of active protein or drug molecules. Such GO-based gene delivery approach can also be useful to direct cell behavior in well-defined 3D hydrogel microenvironment system for advanced tissue engineering applications. In fact, the delivery of genes using fGO can function not only as gene complexing agents but also as structural scaffolds for tissue engineering. This combination of GO/DNA therapy and tissue engineering within a single system can be a new strategy for regenerative medicine.

Although the study findings exemplify the beneficial effects of low modulus hydrogel-based gene therapy treatment, further studies are needed to elucidate the long-term effects of the treatment on heart function. It is important to investigate whether multiple administration of the therapy will invoke further salutary effects to the infarcted heart. To our advantage, the GelMA/fGO hydrogel based gene delivery system can be potentially used for co-delivery of multiple therapeutic genes, bioactive small molecules and peptides. Slow delivery of combination of such therapeutics within the same formulation may augment the protein expression or biofunctional activities of the delivered materials. Another crucial factor that needs further studies is to understand the long-term fate of GO in the host system. Studies in this direction have demonstrated that polymer functionalized GO remains in the host body for a long time post-administration, but it does not significantly invoke the in vivo toxicity. However, intravenous administration of GO nanoflakes in mice in high concentration (4 mg/kg) for 5 consecutive days induced mutagenesis. Also, Qu et al. reported GO can increase the level of reactive oxygen species in macrophages, triggering drastic cell morphologic changes and eventual in vitro necrosis. Thus, special considerations have to be given while optimizing the in vivo dosages and characterizing the stability of surface functionalized GO nanosheets to ensure their long-term biocompatibility and safety.

Taken together, this study demonstrated the postulation that this newly formulated gene-active GO/GelMA hydrogel can take advantage of the unique features associated with GelMA hydrogel and GO-based angiogenic gene delivery system to exhibit enhanced AMI therapeutic efficacy without any significant side effects. In particular, the injectable nanocomposite hydrogels induced in vivo beneficial effects on tissue revascularization at injured site and improved contractile performance, as corroborated by vasculogenesis, scar area analysis and echocardiogram data examinations. The findings from this study also provide insight into the biocompatibility properties of this new therapeutic delivery system for cardiac applications.

MATERIALS AND METHODS

Preparation of Injectable GelMA Hydrogel Carrying GO/DNA Nanocomplex. Preparation of Hydrogel. Low methacrylated GelMA was synthesized as reported earlier. Briefly, gelatin at 10% (w/v) was added in PBS at 50 °C and stirred for 1 h to completely dissolve it. While stirring, methacrylate anhydride (MA) was added dropwise (0.25% vol %) to the gelatin solution. After 2 h, the reaction was stopped by diluting the solution with PBS. The diluted mixture was dialyzed against distilled water with a dialysis membrane (Mₘ cutoff of 12–14 kDa) for 7 days to remove unreacted MA and salts. The resulting solution was subsequently frozen in liquid nitrogen and lyophilized to obtain the final product (~20% methacrylation).

Preparation of GO/DNA Nanocomplex Formation. GO nanosheets were purchased from Nanocs, Inc. and functionalized to low molecular weight branched PEI using method used elsewhere. Briefly, to bind low molecular weight PEI (Mₘ = 1.8 kDa) to the carboxyl groups of GO by 1-ethyl-3-[3-(dimethylamino)propyl]carbodiimide hydrochloride (EDC)/N-hydroxysuccinimide (NHS) coupling, GOs were suspended in deionized water by sonication, and EDC and NHS were added to the GO solution (0.5 mg/ml, 1 mL). Then, 100 μL of triethylamine was added to a PEI solution in deionized water. The PEI solution was added to the GO prepared (1 mL, 0.5 mg/mL) and stirred for 24 h. The resulting PEI–GO solution was dialyzed against a 3.5 kDa cutoff dialysis membrane for 48 h to get rid of the unreacted components. The surface charge of GO, PEI–GO (fGO), and PEI–GO/DNA (fGO/DNA) complexes with different N/P ratios in PBS buffer were confirmed by zeta potential measurements using Zeta Potential Analyzer (Brookhaven Instruments Corporation, Holtsville, NY). The samples were prepared at various N/P ratios by the addition of fGO suspensions to the plasmid DNA solutions in PBS buffer. For the study, plasmid DNAs, carrying either VEGF_165 (Originex) or GFP expressing genes (Promega) driven by a cytomegalovirus (CMV)
immediate early promoter, were used as described in earlier studies.\textsuperscript{13,42} The final plasmid DNA concentration was adjusted to 33 μg/mL, and the mixtures were incubated for 30 min to form the electrostatic nanocomplexes (fGOOGFP or fGOVEGF) prior to transfection. The zeta potential, Transmission electron microscopy (TEM) was used to obtain the size characterization. The nanocomplexes were suspended in PBS and analyzed on CM200 FEG-TEM (Philips, Markham, Ontario, Canada).

Preparation of GO/GelMA Hydrogel. Lyophilized GelMA (5 wt%) and photoinitiator (0.25 wt%), 2-hydroxy-1-(4-hydroxyphenoxy)phényl-2-methyl-1-propanone (Irgacure 2959; CIBA chemical) were first dissolved in PBS at 80 °C for 30 min. Then, 75 μL of this prepolymer solution, along with fGOVEGF (16), was pipetted into the space between two glass slides separated by a 1 mm spacer and exposed to UV at 6.9 mW/cm² (wavelength 360–480 nm) for 15 s similar to the method used earlier.\textsuperscript{13} The compressive modulus and rheological properties of the formed hydrogel was analyzed using Instron 5524 mechanical analyzer (Instron, Canton, MA) and AR-G2 Rheometer (TA Instruments) respectively.\textsuperscript{13,42}

In Vivo Cardiomyocyte Transfection and Biofunctional Analysis. Cyto-

toxicity Assay. First, the cardiomyocyte transfection efficiency, gene delivery efficiency of fGOGFP with three different formulations was analyzed using MTS cell proliferation assay (Promega) according the manufacturer’s instructions.\textsuperscript{41} This was followed by release kinetics study of fGO/DNA nano-complexes from entrapped GelMA over time. The data confirmed rapid release of the entrapped fGO/DNA nanocomplexes from GelMA of the fGO in physiological conditions was followed by gel retardation assay. The experiment was performed also to confirm the successful binding of fGO with DNA molecules where the DNA bound nanocomplexes show retardation in gel electrophoresis.

Cardiomyocyte Transfection Study. To optimize the transfection efficiency, gene delivery of different fGO/DNA formulations was analyzed using MTS cell proliferation assay (Promega) according the manufacturer’s instructions.\textsuperscript{41} This was followed by release kinetics study of fGO/DNA nano-complexes from entrapped GelMA over time. The data confirmed rapid release of the entrapped fGO/DNA nanocomplexes from GelMA of the fGO in physiological conditions was followed by gel retardation assay. The experiment was performed also to confirm the successful binding of fGO with DNA molecules where the DNA bound nanocomplexes show retardation in gel electrophoresis.

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Assessment of In Vivo Therapeutic Efficacy of the Developed GO/DNA Based Hydrogel. Confirmation of In Vivo Gene Delivery. To confirm the in vivo gene delivery to the myocardial tissue using GelMA based GO gene delivery system, 3 animals were intramyocardially injected with fGO\textsubscript{VEGF}/GelMA hydrogel. In vivo Lac Z expression at the injection sites was detected using X-gal (bromo-chloro-indolyl-galactopyranoside) by sacrificing the animals 7 days post administration as previously described.\textsuperscript{52} Confirmation of Functional Efficacy. To perform this, myocardially infected rats were divided into 4 groups. The G\textsubscript{group} (n = 7) received 300 μL of only GelMA, GG group (n = 7) received DNA\textsubscript{VEGF}/GelMA and GG/fGO\textsubscript{VEGF}/GelMA (N/P ratio 16), where the last 2 groups received 20 μg of plasmids per animal following the protocol mentioned above. The control group received 300 μL of PBS only. To understand the functional efficacy of the different treatment groups, animals were analyzed by (a) immunohistochemistry to examine neovascularisation, (b) histological analysis to detect scar area, and (c) echocardiography to examine cardiac performance 2 weeks post treatment.

(a) Immunohistochemistry to detect neovascularisation: Capillary and arteriolar densities in the peri-infarct regions were quantified by tracing neovascularized regions. Immunohistochemical staining was performed with anti-PECAM1 (Santa Cruz Biotechnology, Santa Cruz, CA) and smooth muscle α-actin positive microvessels per mm\textsuperscript{2} area for each group of animals. The control group received 300 μL of PBS only. To understand the functional efficacy of the different treatment groups, animals were analyzed by (a) immunohistochemistry to examine neovascularisation, (b) histological analysis to detect scar area, and (c) echocardiography to examine cardiac performance 2 weeks post treatment.

(b) Histological analysis of scar areas: Paraffin embedded 5 μm thickness samples were deparaffinized and stained with collagen-specific Sirius Red dye for detection and quantification of fibrosis areas (in red) in the ventricular region using ImageJ-1.41 software as reported earlier.\textsuperscript{59}

(c) Echocardiography for cardiac performance evaluation: Transthoracic echocardiography studies were performed using echocardiographic instrument (Sonosite, Seattle, WA) after sedating the animals with isoflurane. Left ventricular ejection fractions (EF) were calculated from the echocardiogram in all the four groups 2 days (baseline) and 2 weeks post-infection.\textsuperscript{59} Quantitative variables are presented as mean ± standard deviation (SD) from independent experiments as described in the figure legends. Statistics were performed using two-way and/or one-way analysis of variance (ANOVA) by Bonferroni’s multiple comparison post-hoc test. All statistical analyses were performed with Prism 5 (GraphPad Software). P-value <0.05 was considered significant.

Conflict of Interest: The authors declare no competing financial interest.

Supporting Information Available: Rheological properties of the hybrid injectable GO/GelMA hydrogel, photo-cross-linkable nature of hydrogel and its biocompatibility, TEM images of GO nanocomplexes and zeta potential, cytotoxicity analysis with cells, GO/DNA release kinetics from hydrogel and the transfection efficiency, quantification of secreted VEGF protein over-expression, in vivo immunohistological and histological staining pictures. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES AND NOTES


