



Research Article

# Preparation and characterization of dopamine–sodium carboxymethyl cellulose hydrogel

Yining Chen<sup>1,2</sup> · Guolian Cui<sup>1,2</sup> · Nianhua Dan<sup>1,2</sup> · Yanping Huang<sup>1,2</sup> · Zhongxiang Bai<sup>1,2</sup> · Changkai Yang<sup>1,2</sup> · Weihua Dan<sup>1,2</sup>

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## Abstract

In order to prepare a biocompatible tissue adhesive and sealant with high adhesion properties, dopamine (DA) was grafted onto sodium carboxymethyl cellulose (CMC) to obtain catechol-modified CMC–DA by carbodiimide chemistry method, and then CMC–DA hydrogels was prepared by self-cross-linking. The UV–Vis spectroscopy, FTIR and <sup>1</sup>H NMR results showed that dopamine was successfully introduced into CMC and the degree of substitution of dopamine in the CMC–DA hydrogels was 5%, 10.5% and 15%, respectively. SEM observation indicated that CMC–DA possessed porous structures. Cytotoxicity experiments showed that CMC–DA has good biocompatibility. The introduction of DA could further improve the biocompatibility of hydrogel. Bulk adhesion property of the hydrogels was studied by lap shear tests. Results showed that the adhesion strength of CMC was improved indeed after modified by dopamine.

**Keywords** Dopamine · Sodium carboxymethyl cellulose · Hydrogel · Bio-adhesion

## 1 Introduction

Sutures are commonly used for wound closure and bleeding control; however they still have limitations such as, high infection rate, inconvenience in handling, and concern over possible transmission of blood-borne disease through the use of needles. One of the challenges of tissue engineering consist on the design and development of biocompatible tissue adhesives and sealants with high adhesion properties to repair or attach devices to tissues [1, 2]. Biological adhesive is a kind of biomedical material that can be filled, closed and glued to the wound. It has both the bonding properties of general adhesives and other functions to meet the requirements in biomedical applications [3, 4].

Sodium carboxymethyl cellulose (CMC) is a derivative of cellulose after carboxymethylation, also known as cellulose gum, a kind of natural polysaccharide, which has been

widely used in the fields of food, medicine, paper, chemical, and so on [5–7]. Because of its good biocompatibility, low toxicity, low immunogenicity and biodegradability, CMC has been widely applied in the field of tissue engineering [8, 9]. CMC belongs to the anionic linear polymer material, which has good water solubility during to the carboxymethyl structure on the piranosine unit and can form a transparent viscous liquid after dissolving in water. In view of the low adhesion strength of single CMC and its large number of active groups such as carboxyl and hydroxyl groups, it is necessary to improve adhesion properties and biocompatibility through modification.

Dopamine (3,4-dihydroxyphenylethylamine, DA) is a derivative of tyrosine in mussel mucin containing catechol functional groups, giving it unique bioadhesive properties [10, 11]. In recent years, dopamine has been widely used for the preparation of bio-adhesives primarily inspired by the superior adhesion of mussels in the ocean [12]. Mussel

✉ Nianhua Dan, dannianhua@scu.edu.cn; ✉ Weihua Dan, danweihua\_scu@126.com | <sup>1</sup>Key Laboratory for Leather Chemistry and Engineering of the Education Ministry, Sichuan University, Chengdu 610065, Sichuan, China. <sup>2</sup>Research Center of Biomedical Engineering, Sichuan University, Chengdu 610065, Sichuan, China.



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is a kind of marine organism widely existing on the coast and offshore. It can rely on the “foot plate” formed by secreted filaments to adhere firmly to various inorganic and organic surfaces in seawater [13]. The strong adhesive properties possessed in wet conditions are in line with the requirements for the use of tissue adhesives. Bio-adhesives based on biomimetic studies of mussel foot pad are considered to be the most suitable tissue adhesives for clinical needs [14].

The combination of dopamine and CMC can improve the adhesive properties and biocompatibility of natural polysaccharides. In this study, the amino groups of dopamine and the carboxyl groups of CMC were cross-linked by an amidation reaction under the action of carbodiimide (EDC). Thus, dopamine was introduced into the CMC molecular chain to prepare a new type of bio-adhesive hydrogel after self-cross-linking, and the physicochemical properties, adhesion strength and biocompatibility of the bonded hydrogel were characterized.

## 2 Experimental

### 2.1 Materials

Dopamine hydrochloride and carboxymethyl cellulose sodium (65–80% carboxyl degree, average  $M_w$  was about 250,000, Sodium (ICP) was 6.5–9.5%) were purchased from Sigma-Aldrich (St. Louis, MO, USA); 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide (EDC), *N*-hydroxysuccinimide (NHS) and 2-(*N*-morpholine) Ethanesulfonic acid (MES) were purchased from Gongjia Chemical Technology Co., Ltd. (Shanghai, China), gelatin was purchased from Jinshan Chemical Reagent Co., Ltd. (Chengdu, China). Unless otherwise indicated, other chemicals and reagents were purchased from Kelong Chemical Reagent Co., Ltd. (Chengdu, China). Mouse fibroblast L929 was purchased from Huaxi State Key Laboratory of Biotherapy (Chengdu, China).

### 2.2 Preparation of hydrogels with different degrees of dopamine substitution

The CMC was weighed and put in a three-necked flask with 100 ml of MES buffer solution. The mixture was stirred under a 35 °C water bath, resulting in complete dissolution of the CMC to a mass fraction of 2.5%. A certain amount of NHS and EDC was added in order to activate the cross-linking reaction, after 20 min, dopamine was added. The pH of the reaction system was adjusted to about 5.0 with dilute hydrochloric acid. Nitrogen protection was always applied throughout the reaction and the reaction time lasted 24 h. After the reaction was completed, the reaction product was loaded

into a dialysis bag with a molecular weight of 3000 Da, dialyzed against distilled water for 3 days, and changed every 4–5 times. The sample was then freeze-dried and stored for future use. Before use, the lyophilized CMC–DA sample was dissolved in a phosphate solution (PB) to make a 20% (w/w) solution, and the solution was stored at room temperature for a period of time to obtain the adhesive hydrogel which was labeled as CMC–DA.

### 2.3 UV–visible spectroscopic analysis

Freeze-dried CMC–DA was dissolved in PB buffer to prepare a solution with a mass concentration of 0.25 mg/mL. A full-spectrum scan was performed in an ultraviolet–visible spectrophotometer (LAMBDA25, PE CO., American) and the absorbance values at 280 nm were measured. The degree of substitution of dopamine in CMC–DA was determined using a standard curve method.

### 2.4 Measurement of FTIR spectra

The approximately 2 mg of each specimen mixed with about 100 mg KBr were pressed into tablets. Fourier transform infrared (FTIR) spectra were measured from the tablets using a FTIR spectrophotometer (Nicolet iS10, Thermo Scientific CO., America). The spectra were collected from 4000 to 400  $\text{cm}^{-1}$  at a rate of 32 scans per spectrum and a resolution of 4  $\text{cm}^{-1}$  at room temperature with a humidity of around 65%.

### 2.5 $^1\text{H}$ NMR spectroscopy

CMC–DA samples were dissolved in  $\text{D}_2\text{O}$  respectively, and the  $^1\text{H}$  NMR spectra were carried out on a Bruker AVII-400 MHz (Bruker, Switzerland).

### 2.6 Determination of equilibrium swelling ratio

The lyophilized CMC–DA hydrogel sample was weighed and recorded as  $m_d$ , then immersed in a PB buffer solution and placed in a 37 °C water bath to swell the hydrogel to equilibrium. After adsorption water on the surface of the sample was removed with filter paper, sample was weighed and recorded as  $m_w$ . Three parallel data were measured for each hydrogel sample. The equilibrium swelling ratio (SR) was calculated according to the following formula [15]:

$$\text{SR} (\%) = \frac{(m_w) - (m_d)}{m_d} \times 100$$

## 2.7 Micromorphology analysis

The morphologies of CMC–DA hydrogel samples were characterized by scanning electron microscopy (JSM-7500F, JEOL, Japan). The specimens were sputter-coated with aurum, and the images were acquired at an accelerating voltage of 5 kV.

## 2.8 Evaluation of in vitro biocompatibility

The biocompatibilities of CMC–DA hydrogel samples were investigated with L929 fibroblast cells using cell proliferation assay and confocal laser scanning microscopy (CLSM). Briefly, the samples were sealed and sterilized using a  $^{60}\text{Co}$  irradiation, and thereafter were soaked in culture media and incubated at 37 °C for 24 h, to prepare sample solutions. In the meantime, L929 fibroblast cells were cultured in RPMI 1640 medium supplemented with 1% (v/v) antibiotic solution and 10% calf serum in 96-well plates, for 24 h at 37 °C in 5%  $\text{CO}_2$  atmosphere. After that, the culture medium was replaced with the sample solution, and then further incubated for additional 1, 3, and 5 days at 37 °C in 5%  $\text{CO}_2$  atmosphere. At each time point, 20  $\mu\text{l}$  of 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazoliumbromide (MTT) was added, and incubated at 37 °C for 4 h to allow the formation of formazan crystals. Subsequently, DMSO (200  $\mu\text{l}$ /well) was added to dissolve the formazan crystals, and the optical density (OD) at 492 nm was then measured using a microplate reader (Model 550, Bio Rad Corp. USA). The biocompatibility of CMC–DA hydrogel samples was further evaluated and observed by CLSM. Briefly, L929 fibroblasts were cultured on pADM scaffolds for 3 days at 37 °C in 5%  $\text{CO}_2$  atmosphere. Subsequently, the cells were fixed with 4% paraformaldehyde in PBS for 30 min at room temperature. After washing by PBS, the cells were stained with 4,6-diamidino-2-phenylindole (DAPI), and then visualized by a confocal laser scanning microscope (CLSM;TCS SPII, Leica).

## 2.9 Determination of adhesion strength

The adhesion strength of CMC–DA hydrogel was measured according to ASTM F2255-03. A 75 mm  $\times$  25 mm slide was used as the substrate and was dipped in a gelatin solution with a mass fraction of 20% and allowed to air dry for 2 h at room temperature. Then freeze-dried sample of CMC–DA was dissolved in PB buffer to prepare a solution with a mass concentration of 20 mg/ml, which was smeared on gelatin-treated slides afterwards. The length, width, and thickness of the bonding sites were sequentially 25 mm, 25 mm, 0.5 mm, cured at room temperature for 2 h, then transferred to a 37 °C, relative humidity of 80% or more in the incubator for 1 h. Subsequently, the lap shear strength

of the hydrogel was measured with a universal electronic tensile machine (GT-AL-7000S, GOTECH Co., Ltd. Taiwan), and the tensile speed was 5 mm/min. At least 5 sets of parallel data were measured for each sample. The results were averaged [16].

## 2.10 Statistical analysis

Statistical analysis was conducted on SPSS 19.0. Differences between groups were considered statistically significant at  $P < 0.05$  (\*).

## 3 Results and discussion

### 3.1 Determination of dopamine substitution in CMC–DA hydrogels

Figure 1 shows the UV–vis spectra of CMC, dopamine and CMC–DA solutions with different degrees of substitution of dopamine. It can be seen that the dopamine solution has the maximum absorption peak at 280 nm, which is a characteristic absorption peak of the catechol group. Since CMC does not contain a chromophoric group in its molecular structure, no significant absorption peak was observed in the 200–600 nm range. However, after the CMC was grafted with dopamine, the catechol group was introduced into the molecular chain, resulting in a characteristic absorption peak similar to dopamine, a distinct absorption peak at 280 nm, which indicated initially that dopamine has been successfully introduced into the CMC molecular chain under the influence of EDC/NHS. The mechanism of preparation of CMC–DA was showed in Fig. 2. In the cross-linking process, EDC/NHS only activated the carboxyl groups of the CMC to form the amide

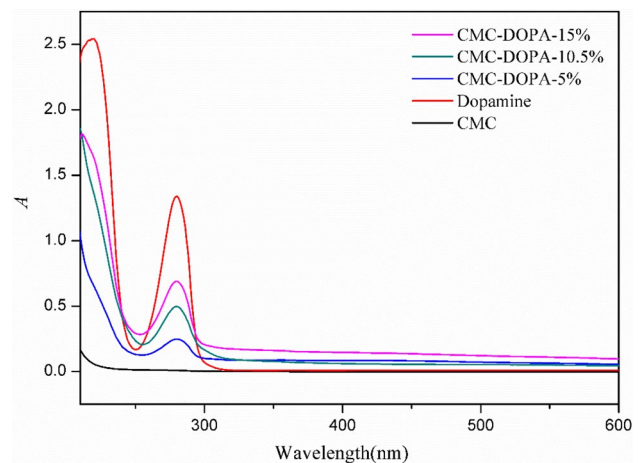
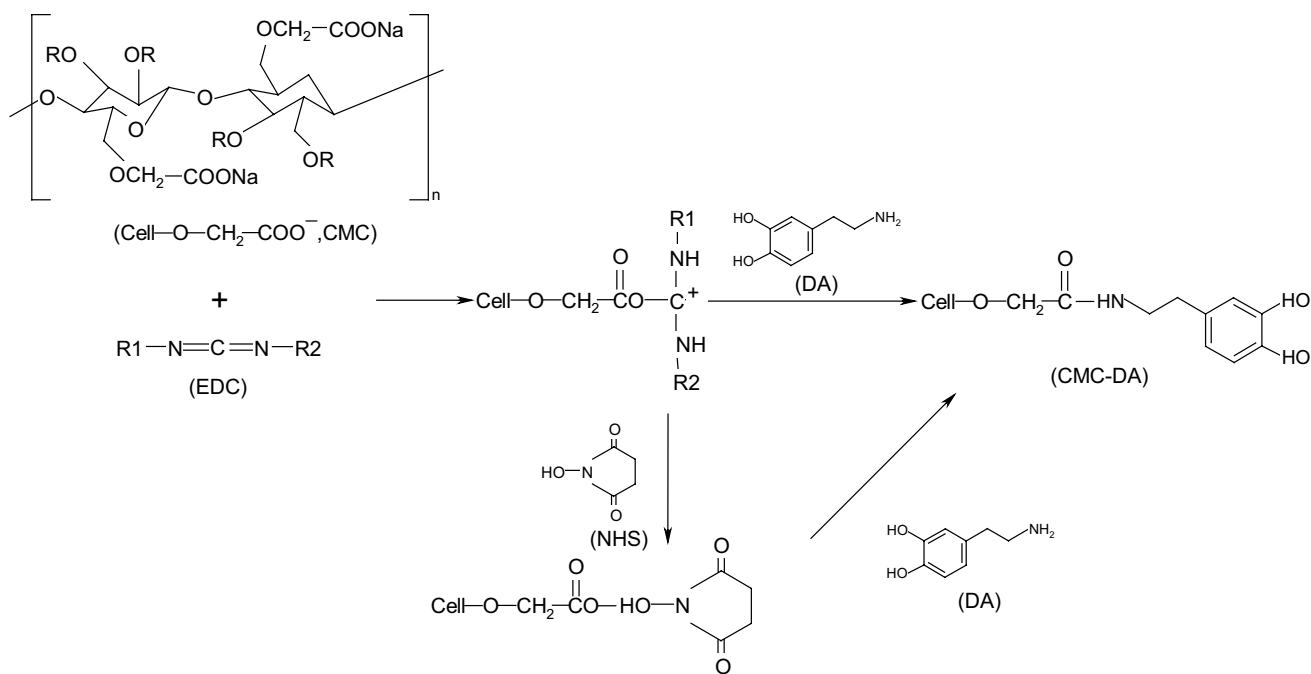


Fig. 1 UV–Vis spectra of CMC, dopamine and CMC–DA hydrogels with different DS



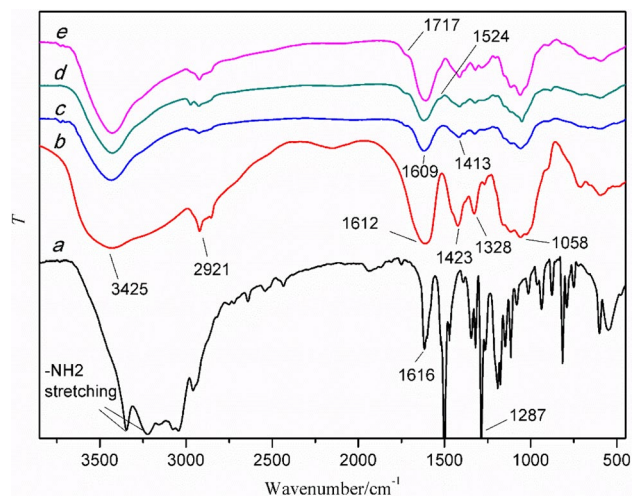
**Fig. 2** The mechanism diagram of preparation of CMC-DA

bonds with the amino groups on the dopamine, which itself was not a part of the connection in the cross-linked molecule. Upon completion of the cross-linking reaction, it turned into a water-soluble urea derivative with very low cytotoxicity, which can be removed by cleaning [17]. This cross-linking property could avoid the residual of toxic substances in the conventional cross-linking and is therefore very suitable for the cross-linking of biomaterials. According to the report [18], if the structure of dopamine catechol was oxidized to o-benzoquinone or semiquinone structure, the absorption peak would appear at 350 nm to 450 nm in the UV-Vis spectra. Since no appreciable absorption peak was observed in this wavelength range in Fig. 1, indicating that the catechol groups in CMC-DA were not oxidized, which is the basis for the strong binding properties of the catechol groups. That is, the catechol group should not be oxidized to o-benzoquinone or semiquinone structure in order to ensure that the prepared adhesive hydrogel has a greater adhesion strength [19–21]. Since the dopamine catechol structure has a distinct absorption peak at the wavelength of 280 nm, the content of catechol groups could be calculated by measuring the absorbance at 280 nm of the sample, so as to calculate the dopamine substitution degree of the material [22, 23]. The calculated results showed that the degree of substitution of dopamine in the prepared CMC-DA was 5%, 10.5%, and 15%, respectively, so the prepared hydrogels with

different dopamine contents are successively recorded as CMC-DA-5%, CMC-DA-10.5% and CMC-DA-15%.

### 3.2 FTIR analysis

Figure 3 shows the FTIR spectra of dopamine, CMC, and CMC-DA. The characteristic peak observed at around  $1616\text{ cm}^{-1}$  belongs to the stretching vibration peak of the C=C bond in the dopamine benzene ring, and the peak around at  $1287\text{ cm}^{-1}$  belongs to the stretching vibration



**Fig. 3** FTIR spectra of dopamine (a), CMC (b), CMC-DA-5% (c), CMC-DA-10.5% (d) and CMC-DA-15% (e)

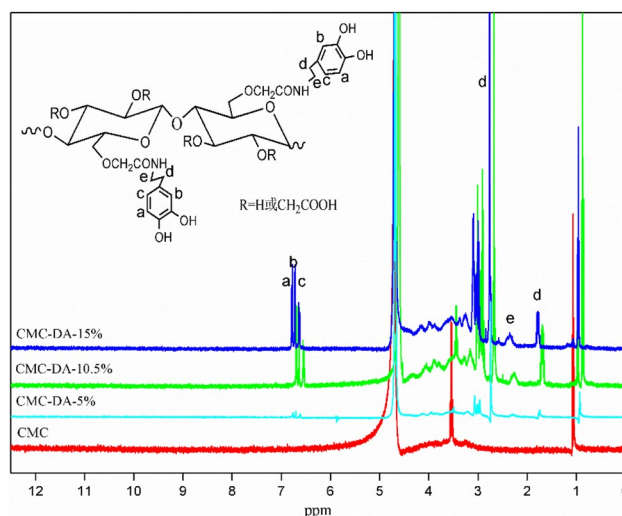
peak of C–O in the catechol structure [24]. Because the carboxyl groups in CMC existed in the form of sodium salt, then formed the carboxylate negative ion  $-\text{C}(\text{O})\text{O}^-$ , two double bonds were the same, there was no distinction between single and double bonds, thus asymmetric and symmetric stretching vibration peaks were observed at  $1612\text{ cm}^{-1}$  and  $1423\text{ cm}^{-1}$ , respectively. The peak at  $1058\text{ cm}^{-1}$  was the stretching vibration peak of C–O–C in the structural unit of CMC, and the peaks at  $3425\text{ cm}^{-1}$  and  $2921\text{ cm}^{-1}$  were due to the stretching vibration of O–H bond and the asymmetric stretching vibration of C–H bond. Comparing the spectra of CMC–DA and CMC, the intensity of the asymmetric and symmetric stretching vibration peaks assigned to  $-\text{COONa}$  in CMC–DA was significantly reduced, and a weak peak appeared at  $1524\text{ cm}^{-1}$  which was assigned to amide II. The vibrational peak of the band indicated that the amino groups of dopamine and the carboxyl groups in the CMC have undergone an amidation reaction, and a part of the  $-\text{COONa}$  groups in the CMC was consumed. The spectrum of CMC–DA showed an absorption peak at  $1717\text{ cm}^{-1}$ , which might be assigned to the vibration absorption peak of  $-\text{COOH}$  because the  $-\text{COONa}$  group in CMC might be bound to  $\text{H}^+$  under acidic conditions and hydrolysis to  $-\text{COOH}$  groups after a series of reactions.

### 3.3 NMR analysis

NMR is an important method to identify the structure of organic compounds. The NMR spectra of CMC and CMC–DA with different dopamine substitution degrees were showed in Fig. 4. The absorption peak at  $\delta 4.7$  was assigned to the hydrogen of  $\text{D}_2\text{O}$ , and the multiple peaks at  $\delta 3.4$ – $3.8$  were assigned to the hydrogen on the polysaccharide ring in the molecular structure of CMC.  $\delta 1.8$  and  $\delta 2.75$  belong to the methylene hydrogen adjacent to the benzene ring in the structure of dopamine, while  $\delta 2.3$  belongs to the hydrogen adjacent to the amino group in dopamine [15]. After reacting with dopamine, new triple peaks at the  $\delta 6.35$ – $6.8$  appeared in CMC–DA compared with CMC (see a, b, c in Fig. 4), which belonged to phenyl protons, and is a characteristic absorption peak of hydrogen on the benzene ring structure of dopamine [25, 26]. Thus, it is demonstrated that dopamine was successfully introduced into the molecular chain of CMC. The result was in keeping with that of UV–Vis spectra.

### 3.4 Determination of the equilibrium swelling ratio of CMC–DA

Swelling ratio is an important property of hydrogels, which has an important influence on the transportation



**Fig. 4**  $^1\text{H}$  NMR spectra of CMC and CMC–DA hydrogels with different DS

**Table 1** Equilibrium swelling ratio of CMC–DA hydrogels

Sample	SR (%)
CMC	–
CMC–DA-5%	$2377 \pm 533^{\text{a,b}}$
CMC–DA-10.5%	$2758 \pm 27^{\text{a,b}}$
CMC–DA-15%	$3398 \pm 364^{\text{a}}$

<sup>a</sup>Compared with CMC,  $P < 0.05$

<sup>b</sup>Compared with CMC–DA-15%,  $P < 0.05$

of nutrients, the exchange of moisture and oxygen. Table 1 showed the results of the equilibrium swelling ratio measurement of the CMC–DA hydrogel. As can be seen from Table 1, the prepared CMC–DA hydrogels all had a high equilibrium swelling ratio and were capable of absorbing a large amount of moisture, which might contribute to the cell's metabolism and proliferation. From the statistical analysis of the equilibrium swelling ratio, it can be seen that each group of CMC–DA has a significant difference compared with CMC. At the same time, the CMC–DA-5% and the CMC–DA-10.5% have significant differences, respectively, compared to the CMC–DA-15%. Together, these two results indicated that higher amounts of dopamine added favored gelation of CMC–DA and could significantly increase the equilibrium swelling ratio of the material. In addition, the result showed that the equilibrium swelling ratio of CMC–DA increased with the increase of dopamine substitution degree, owing to the introduction of dopamine increased the hydroxyl content, which improved the hydrophilicity of the hydrogel and led to an increase in the equilibrium swelling ratio [15]. All CMC–DA samples had good swelling properties. As a bio-adhesive, it is

conductive for CMC–DA to provide a suitable environment for the adhesion and proliferation of skin fibroblasts and it is expected to promote tissue regeneration.

### 3.5 Micromorphology of CMC–DA

It is known that there are some possible interactions of the catechol of DA [27]. Many researchers have done a lot of researches on the mechanism of the reaction of DA. The dihydroxy functionality of catechol enables it to form strong hydrogen bonds. And the benzene ring of catechol is capable of interacting with other aromatic rings through  $\pi$ – $\pi$  electron interaction [28]. In addition to the non-covalent cross-linking, covalent cross-linking also exists. Since catechols are easily oxidized to its quinone form in an oxygen rich and basic environment. When catechol is oxidized, it becomes highly reactive and can participate in intermolecular covalent cross-linking, resulting in the polymerization of DA [28]. For CMC–DA, DA had been covalently grafted onto CMC by the action of EDC/NHS without prejudice to the structure of DA catechol. Therefore, the active catechol groups on CMC–DA had high reactivity, could form hydrogen bonds,  $\pi$ – $\pi$  electron interaction, and covalent crosslinks, thereby forming crosslinks between CMC–DA molecular chains, which promoted gelation of CMC–DA hydrogel, as shown in Fig. 5.

Figure 6 showed the SEM image of the CMC–DA hydrogel after lyophilization. It can be seen that the prepared hydrogel had a spatial three-dimensional network structure with a unique microscopic pore structure. At higher substitution, differences of microstructure between all samples had been observed, but the porous network structure of each sample was still maintained. The possible reason is that the increasing of dopamine substitution degree provided more contact probability of reactive groups with each other, thereby promoting mutual cross-linking between the internal substances, and macroscopically exhibiting changes in the internal network structure of the hydrogel. The quantitative morphological

characterization was performed on the SEM observation of the samples using Image J. The results showed that the average pore diameters of CMC, CMC–DA-5%, CMC–DA-10.5% and CMC–DA-15% were about 112, 130, 103, 93  $\mu\text{m}$  respectively. It is known that, when the pore diameter is larger than 80  $\mu\text{m}$ , it is very favorable for cell growth and proliferation [29, 30], indicating that CMC–DA hydrogels might be suitable for cell growth.

### 3.6 Cytotoxicity test of CMC–DA

The cytocompatibility of samples was evaluated with both indirect extraction assays (MTT assay) and direct contact assays. Figure 7 showed the relative proliferation rate of L929 fibroblasts in each group using the polystyrene wells as control. It can be seen that with the increase of the degree of dopamine substitution, the CMC–DA showed the better cytocompatibility comparing with CMC. And the CMC–DA-15% group showed the best cytocompatibility among all samples, which might be beneficial from the introduction of dopamine. It can be seen that in the three time nodes of the first day, the third day and the fifth day, there was significant differences between the group of polystyrene well and the CMC, CMC–DA-5%, respectively. This latter finding indicated that CMC was not beneficial to cell proliferation. There was no significant difference between the polystyrene group and CMC–DA-10.5%, CMC–DA-15%, respectively, indicating that the cells proliferated normally. It can be conclude the introduction of dopamine exhibited a positive effect on cell proliferation at the given concentrations. The cytocompatibility of the CMC–DA hydrogel could meet the requirements for body surface application. In addition, the cells cultured on the hydrogel underwent nuclear staining by DAPI, and the observed images were shown in Fig. 8. It can be seen that as the degree of substitution of dopamine increased, the number of cells significantly increased, which was consistent with the results of MTT assay. It is known that dopamine surface contains a large number of hydroxyl groups,

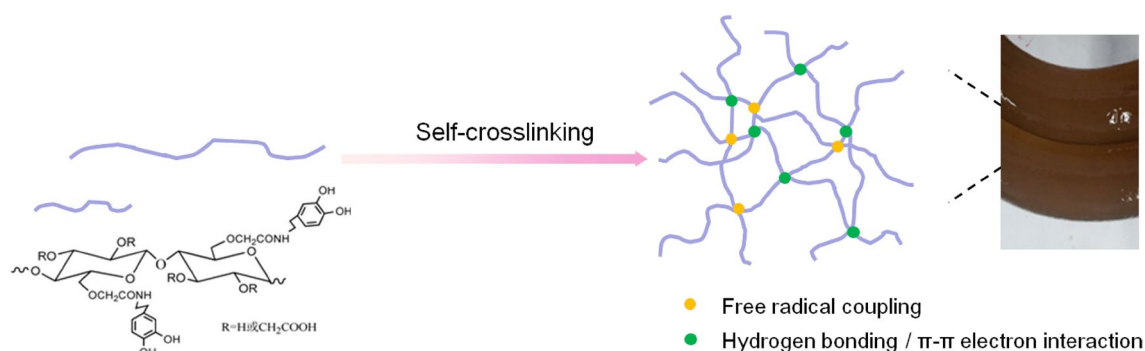
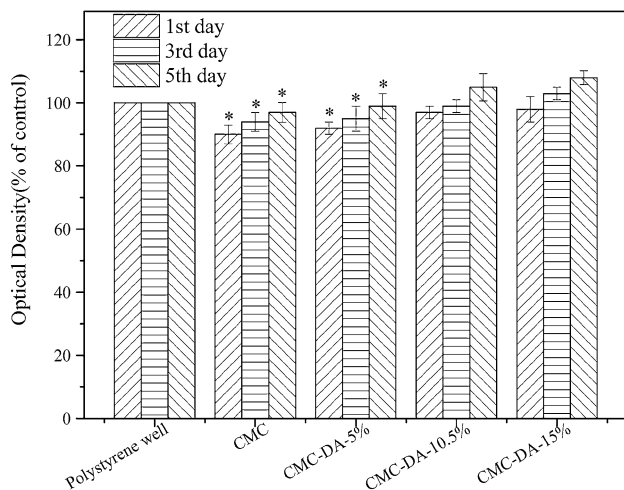
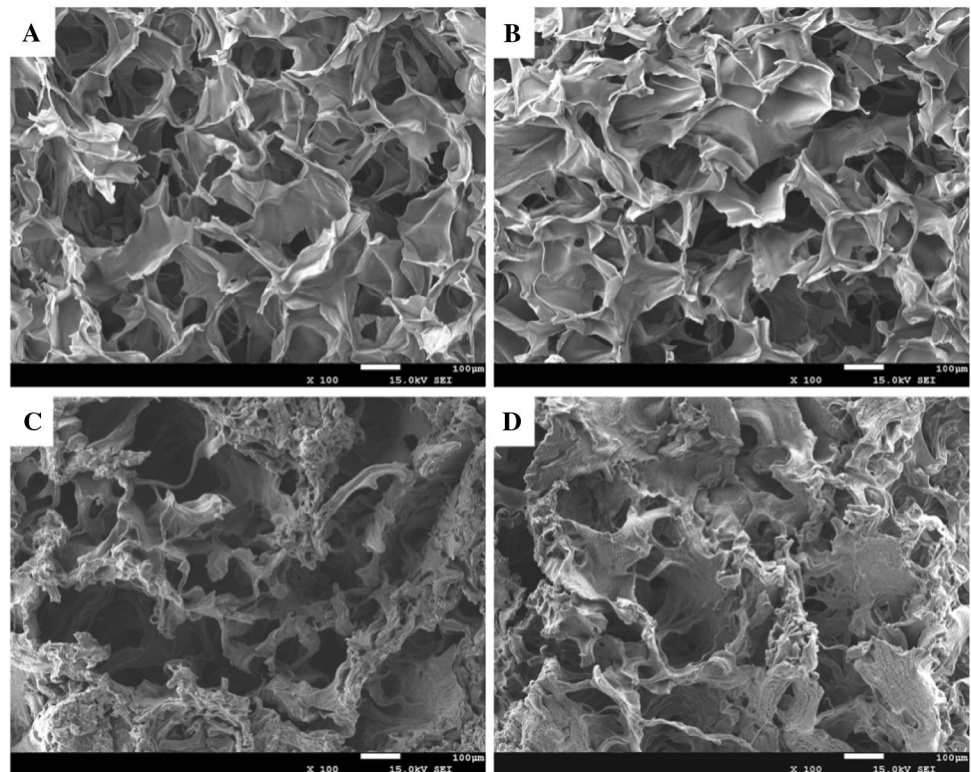


Fig. 5 Mechanism diagram of CMC–DA hydrogel formation

**Fig. 6** SEM micrographs of CMC and CMC-DA hydrogels with different DS ( $\times 100$ ) (**a** CMC, **b** CMC-DA-5%, **c** CMC-DA-10.5%, **d** CMC-DA-15%)



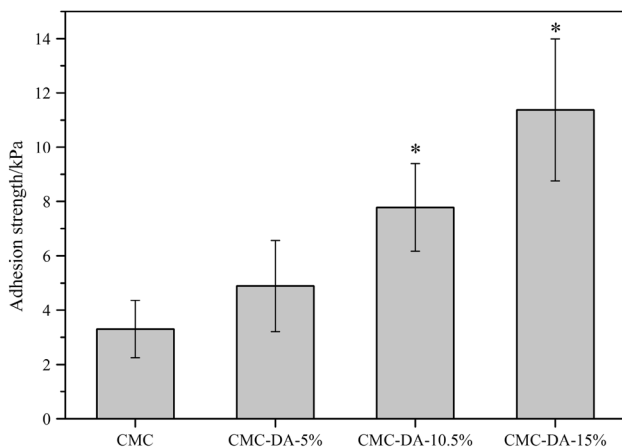
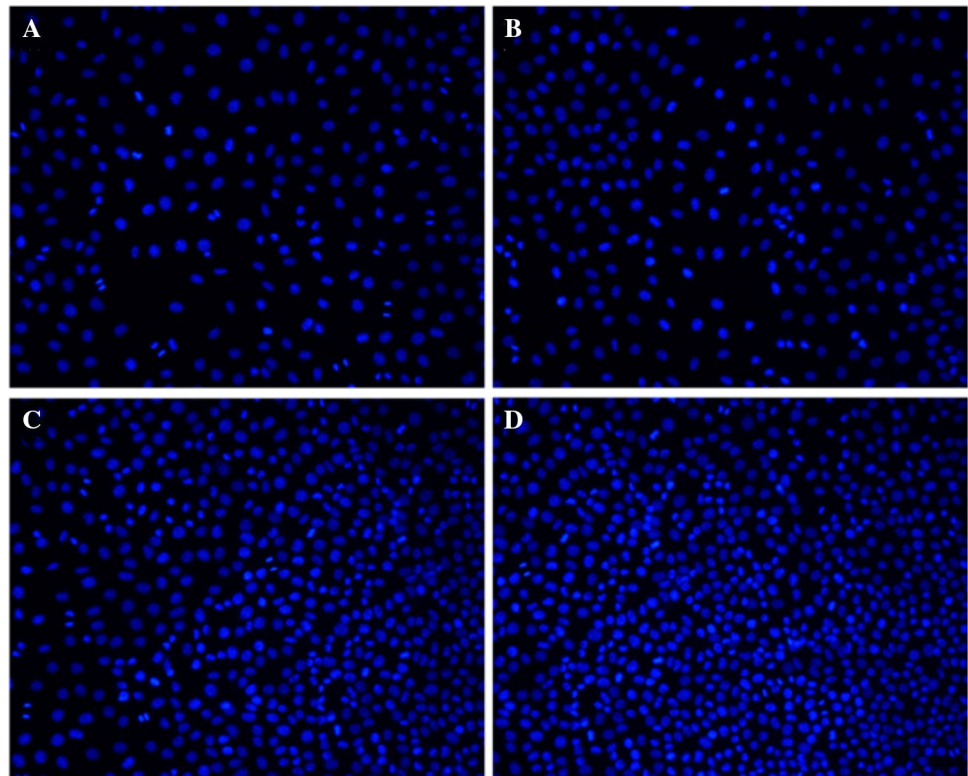
**Fig. 7** Proliferation of L929 fibroblasts cultured in the extraction liquid of CMC and CMC-DA hydrogels with different DS

amino groups and other hydrophilic groups, which could facilitate cell adhesion. More, Dopamine could also promote cell adhesion by binding to extracellular matrix macromolecules such as fibronectin, collagen, laminin, hyaluronic acid or heparin sulfate dopamine [31]. Both MTT and staining results fully demonstrated that dopamine modification has a significant effect on promoting cell adhesion and proliferation, and CMC-DA hydrogels exhibited good cytocompatibility.

### 3.7 Test of adhesion strength

The results of the lap shear strength test of CMC and different dopamine substitution CMC-DA hydrogels was shown in Fig. 9. It can be seen that the lap shear strength of CMC-DA hydrogels was higher than that of CMC. As is shown, there was a significant difference between the CMC group and, CMC-DA-10.5%, CMC-DA-15%, respectively. The results showed that the adhesion strength of hydrogels could be significantly improved by adding appropriate dosage ( $\geq 10.5\%$ ) of dopamine. More, as the dopamine substitution degree increased, the adhesion strength of the hydrogel gradually increased from  $3.31 \pm 1.06$  kPa of CMC to  $11.37 \pm 2.62$  kPa of CMC-DA-15%, which increased nearly 4 times, fully indicating that the introduction of dopamine could significantly improve the adhesion strength of CMC under wet conditions. This result is consistent with the reports in the literature that catechol groups can effectively improve the adhesion strength of natural or synthetic polymer materials such as chitosan [32], sodium alginate [16], hyaluronic acid [33] and polyethylene glycol [34]. It is known that catechols are easily oxidized to its quinone form in an oxygen rich and basic environment [35]. The reason for the enhancement of the adhesion strength of CMC-DA hydrogels might be that under neutral or alkaline conditions, the catechol groups on dopamine were oxidized to catechone or semi-quinone structures, which

**Fig. 8** Fluorescent images of L929 fibroblasts cultured with CMC and CMC-DA hydrogels with different DS (**a** CMC, **b** CMC-DA-5%, **c** CMC-DA-10.5%, **d** CMC-DA-15%)



**Fig. 9** Lap shear strength of CMC and CMC-DA hydrogels with different DS

were highly reactive. For example, quinone tautomerizes to form quinonemethide and  $\alpha,\beta$ -dehydrodopa, leading to the subsequent polymerization of the catechol group [28]. In addition, catechol forms hydrogen bonds through its  $-OH$  groups and  $\pi-\pi$  electron interaction with another benzene in CMC-DA, thus enhancing the cohesion of hydrogel itself [19, 36]. Therefore, the introduction of catechol group into the polysaccharide molecular chain could significantly improve the adhesion strength of polysaccharides under wet conditions.

Good adhesion of CMC-DA was conducive to better covering wounds in further applications.

## 4 Conclusion

The CMC-DA adhesive hydrogel was prepared by self-cross-linking after the amidation reaction between dopamine and CMC via the action of EDC/NHS. The UV-Vis measurement indicated that the degree of substitution of the dopamine was 5%, 10.5% and 15%, respectively. The structure of CMC-DA was characterized by FTIR and  $^1H$ NMR. The results showed that dopamine was successfully introduced into the CMC molecular chain through the amidation reaction. The equilibrium swelling ratio test of CMC-DA hydrogel showed that the prepared hydrogels had good swelling properties, and the swelling ratio increased with the increase of dopamine substitution degree. SEM observation showed that CMC-DA maintained a good pore structure. The adhesion strength of CMC-DA adhesive hydrogel was confirmed to enhanced greatly, it was found that the greater the dopamine substitution degree, the higher the adhesion strength of the hydrogel. The introduction of dopamine could increase the adhesion strength of the polysaccharide under wet conditions. Comprehensive cytotoxicity experiments revealed that CMC-DA had good cytocompatibility, and the introduction of dopamine could significantly improve



the biocompatibility of the material, thus promoting cell proliferation. In conclusion, a bio-adhesive hydrogel with good swelling properties, adhesion properties and cytocompatibility was obtained.

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## Compliance with ethical standards

**Conflict of interest** The authors declare no competing conflict of interests.

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