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Hydrogels with controlled fluorescent properties based on quantum dots and diamine derivatives of polyethylene glycol

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Hydrogels are three-dimensional hydrophilic polymer structures obtained by chemical cross-linking or physical binding. Fluorescent hydrogels based on semiconductor nanocrystals or quantum dots (QDs) are of great interest due to their potential for bioanalytical, biosensor, and microfluidic applications. In the present study an approach to obtaining fluorescent gels with the use of a heterobifunctional cross-linker from water-soluble CdSe/ZnS (core/shell) QDs with the surface functionalized with cysteine and diamine derivatives of polyethylene glycol (PEG) of different lengths has been developed. The structure of the obtained gels was characterized using light, fluorescence, and scanning electron microscopi in comparison with gels obtained by addition of divalent cations. Comparative analysis of the spectral characteristics and fluorescence quantum yield of the obtained gel samples of different structures and morphologies was carried out. It was found that the porosity and optical properties of the obtained gels can be controlled by selecting PEG linkers of different lengths used for chemical gelation.

Keywords: Fluorescent hydrogels, nanocrystals, quantum dots.

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Introduction

Hydrogels based on fluorescent quantum dots (QDs) are promising materials used in different areas, such as catalysis; development of sensors [1], LEDs [2], and targeted drug delivery systems; microfluidics; and bioimaging [3]. Semiconductor QDs have a number of unique optical properties, such as the dependence of the fluorescence wavelength on the nanoparticle size, a quasi-continuous absorption spectrum, and a high fluorescence quantum yield (QY).

Inorganic QD-based hydrogels have unique properties of individual nanocrystals and controlled characteristics of the hydrogel structure and morphology. Methods for obtaining QD hydrogels include controlled destabilization of nanocrystals [4] and their direct binding using linker macromolecules [5] or coordination [6] or covalent bonds [7]. One of the most common methods of gelation is the addition of di- and trivalent cations to the nanocrystals [8,9]. The use of controlled destabilization yields stable gels; however, their structure is difficult to control and may change irreversibly, whereas the use of organic linker molecules that interact with nanocrystals allows the distance between them and the morphology of the obtained structures to be controlled, which considerably extends their applicability [10].

The development of composite materials consisting of a polymer matrix and fluorescent QDs is an important trend in biological and diagnostic research due to the opportunity of their use in designing sensors and bioimaging [11]. The inclusion of QDs into the structure of hydrogels both ensures the mechanical and chemical stability of the QDs and improves the structure of the hydrogels, making them optically active. The porous structure and large surface area of hydrogels allow them to accommodate a significant amount of nanoparticles, preventing their aggregation and increasing the stability of the fluorescence signal [12].

Among the known methods for producing composite hydrogels, the introduction of QDs into the pores of a preformed polymer matrix, the formation of a gel using QDs as structural elements, along with the polymer, as well as direct chemical synthesis of QDs from precursors in a preformed polymer matrix, are the most efficient [12]. Earlier, the possibility of using hydrogels consisting of QDs and cellulose nanofibrils to develop a highly sensitive biosensor for the detection of glutathione in human serum samples was demonstrated [13].

Here, we have developed a one-step method for the preparation of fluorescent hydrogels based on CdSe/ZnS (core/shell) QDs functionalized with cysteine using diamine derivatives of polyethylene glycol (PEG) of various lengths as linker molecules and demonstrated the possibility of controlling the optical properties of the hydrogel by varying its porosity and morphology depending on the length (molecular weight) of the PEG derivatives used.

Materials and methods

Synthesis of CdSe/ZnS (core/shell) QDs The synthesis of CdSe/ZnS QDs was carried out using the so-called phosphine-free one-step colloidal synthesis [14]. Before the synthesis of CdSe cores, a solution of selenium precursor (0.4 M) was prepared, for which purpose a specified amount of selenium powder was placed into a two-neck flask, 16 ml of 1-octadecene (ODE) was added to it, and the remaining oxygen was removed from the flask by short-term evacuation of the system at 120°C, after which the mixture was slowly heated in a flow of argon to 200°C for 1.5 h. As a result of this reaction, a solution of elemental selenium in ODE of intense brown color was obtained, which was subsequently used to obtain CdSe cores.

QD cores were synthesized as follows. 128 mg of cadmium oxide, 1080 μl of oleic acid, and 16 ml of ODE were placed into a 50 ml three-neck flask. This mixture was heated in a flow of argon to 180°C and incubated until the cadmium oxide was completely dissolved to form a solution with a faint yellow color. After that, the reaction mixture was cooled to 120°C and left under vacuum for 30 min to remove the remaining water released in the previous reaction. Then, the vacuum was turned off and the mixture was heated to 270°C in a flow of argon. Upon reaching this temperature, 0.8 ml of a selenium precursor solution was rapidly injected into the flask. After the injection, the temperature of the reaction medium was maintained at 250°C for 5 min, after which the mixture was cooled to 60°C in a flow of argon. At this temperature, 20 ml of methanol was introduced into the flask under a flow of argon, and the resulting emulsion was intensely stirred for 10 min. During this procedure, the remaining unreacted cadmium oleate, which could form by-products during the growth of the ZnS shell, passed into the methanol phase. After 10 min, the emulsion was left to settle until complete separation, after which the top layer of the emulsion was carefully removed using a pipette. The procedure for purifying the reaction mixture *in situ* was repeated two more times, after which the reactor was sealed and the remaining methanol was removed under vacuum at 60°C. Then, the reaction mixture was evacuated for 25 min at a temperature of 120°C, after which the ZnS shell was grown according to the previously described procedure [15] at 180° using zinc 2-ethylhexanoate and thiourea as zinc and sulfur precursors, respectively. After the end of the reaction, the CdSe/ZnS QD solution was cooled to 80°C in a flow of argon, and the QDs were isolated by means of precipitation upon addition of a twofold excess of methyl acetate to the solution and subsequent centrifugation. After additional purification of the product by redissolution and precipitation, purified QDs were obtained, with a mixture of oleic and 2-ethylhexanoic acid residues on the surface as surface ligands. The obtained QDs were dried in a tri-n-octylphosphine oxide matrix for further use.

Preparation of water-soluble CdSe/Zn QDs modified with cysteine 15 mg of CdSe/ZnS QDs in tri-n-octylphosphine oxide was dissolved in 800 μl of chloroform, 1200 μl of methanol was added, and the mixture was centrifuged for 5 min at 14,000 rpm. After this, the supernatant was collected, and this procedure was repeated two more times. Then, the QD pellet was dissolved in 800 μl of chloroform, 300 μl of the solution of DL-cysteine (Sigma Aldrich) in methanol with a polyethylene glycol concentration of 10 mg/ml was added, and the obtained mixture was centrifuged for 10 min at 14,000 rpm. The supernatant was withdrawn and discarded. In this way, the QDs were washed three times in 2000 μl of methanol, with centrifugation for 3 min at 14,000 rpm each time. After that, the supernatant was carefully withdrawn, and the remaining solvent was removed by drying it in a Concentrator Plus vacuum concentrator (Eppendorf). Then, 700 μl of a 0.1 M NaOH solution was added to the pellet under vigorous stirring. The obtained mixture was treated with ultrasound in a water bath for 10 min, after which it was centrifuged for 10 min at 8,000 rpm. The obtained solution of cysteine-modified QDs was transferred to 0.05 M borate buffer (pH 9.5) using a chromatographic column with Sephadex G-25 equilibrated with the appropriate buffer solution.

Development of a method for obtaining hydrogels based on CdSe/ZnS QDs using diamine derivatives of polyethylene glycol The gels consisting of cysteine-modified QDs and linker molecules (PEG) containing two amino groups were obtained by means of a conjugation reaction using 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC) in the presence of N-hydroxysuccinimide (NHS). The reaction was used in two modifications: a one-stage reaction [16] and a two-stage reaction, the effectiveness of which was shown in the conjugation of macrocomplexes of biomolecules [17]. A solution of CdSe/ZnS QDs modified with cysteine (CdSe/ZnS-Cys) in 0.05 M borate buffer (pH 8.5) was used as the initial QD solution. A diamine derivative of PEG with an average molecular weight of 2000 g/mol (poly(ethylene glycol) diamine, Sigma-Aldrich, cat. no. 753084), hereinafter referred to as PEG2000, was used as a linker molecule. Test samples were prepared by adding EDC, NHS, and PEG solutions in 0.05 M MES buffer (pH 6.0) to 100 μl of the QD (CdSe/ZnS-Cys) solution to obtained the molar ratios indicated in Table 1. In sample 4, solutions of EDC and NHS in water were added once more after 1 h of incubation at 25°. As control samples, we used a CdSe/ZnS-Cys QD solution with addition of 0.05 M MES buffer (pH 6.0) in a volume equivalent to the volume of EDC, NHS, and PEG added to the test samples, as well as a QD solution with addition of PEG and 0.05 M MES buffer (pH 6.0) in a volume equivalent to the volume of EDC and NHS in the test samples.

To compare the developed method with the previously known method of gelation with the addition of divalent cations, we also prepared a sample of QDs with addition

Table 1. Scheme of the preparation of hydrogel samples from QDs using diamine derivatives and upon addition of divalent cations

Sample	Molar ratios			Volume added to the reaction mixture, μl					
	EDC/KT	NHS/EDC	PEG/QD	QD	EDC	NHS	0.05 M MES pH 6.0	PEG	0.1 M $MgCl_2$
(1) QD+0.05 M MES, pH 6.0	0	0	0	100.0	0.0	0.0	200.0	0.0	0.0
(2) QD+PEG2000+ 0.05 M MES, pH 6.0	0	0	1000	100.0	0.0	0.0	100.0	100.0	0.0
(3) QD+PEG2000+ EDC + s-NHS (2 stages)	1000 5000	0 10	1000 0	100.0 100.0	50.0 5.0	50.0 5.0	0.0 0.0	100.0 0.0	0.0 0.0
(4) QD+PEG2000+EDC + s-NHS (1 stage)	5000	10	1000	100.0	50.0	50.0	0.0	100.0	0.0
(5) QD+$MgCl_2$	0	0	0	100.0	0.0	0.0	0.0	0.0	200.0

of 0.1 M $MgCl_2$. All the samples were incubated for 24 h at 25°C in the dark. After incubation, the supernatant was withdrawn, and 200 μl of water was added to wash the gels. After 1 h, the supernatant was removed again and the obtained gels were analyzed.

Determination of the stability of gels based on CdSe/ZnS-Cys QDs obtained using diamine derivatives of polyethylene glycol and divalent cations To assess the stability of gels based on CdSe/ZnS-Cys QDs obtained using diamino-PEG, samples 3 and 4 (Table 1) were titrated with a solution of 0.1 M NaOH until the pH became equal to the pH of the initial solution of CdSe/ZnS-Cys QDs (8.5-9.0); a total of 50 μl of 0.1 M NaOH was added. An equivalent volume of 0.1 M NaOH was added to control samples 1 and 2. To assess the stability of hydrogels based on CdSe/ZnS-Cys QDs obtained by adding divalent cations, 200 μl of 0.1 M ethylenediaminetetraacetic acid (EDTA) (pH 8.0) was added to the hydrogel, and the state of the samples was analyzed immediately after the addition of NaOH/EDTA and 24 h after the addition.

Comparison of gels based on CdSe/ZnS-Cys QDs obtained using diamine derivatives of polyethylene glycol with different molecular weights To determine the influence of molecular weight and, hence, the size of linker molecules on the structure of the resulting QD-based hydrogels, we used diamine derivatives of polyethylene glycol with average molecular weights of 400, 2000, and 3400 g/mol (poly(ethylene glycol) diamine, average Mn=400, Sigma-Aldrich, cat. no. 909149; poly(ethylene glycol) diamine, average Mn=2000, Sigma-Aldrich, cat. no. 753084; poly(ethylene glycol) bis(amine), average Mn=3400, Sigma-Aldrich, cat. no. P9906) (PEG400, PEG2000, and PEG3400, respectively). To prepare hydrogel samples, EDC, s-NHS, and one of the PEG derivatives were added to 100 μl of the solution of CdSe/ZnS-Cys QDs in 0.05 M borate buffer (pH 8.5) to obtain the optimal molar ratios determined in the previous experiment (EDC/QD, 5000/1; NHS/EDC, 10/1; PEG/QD, 1000/1, one stage). The mixture was incubated for 24 h at 25°C in the dark; after incubation, the precipitate was washed as described in the previous section, after which the structure of the hydrogels was analyzed.

Analysis of QD-based hydrogels prepared using diamine derivatives of polyethylene glycol and divalent cations using light and fluorescence microscopies After washing, 12.5 μl of the hydrogel samples were applied onto a glass slide, covered with a coverslip, and analyzed using an Axio Observer 3 microscope (Carl Zeiss Microscopy GmbH, Germany) in the light and fluorescence microscopy modes using 20× and 100× lenses. To work with the 100× immersion lens, Immersol 518F immersion oil (Carl Zeiss Microscopy GmbH, Germany) was used. For fluorescence microscopy, an XF 115-2 FITC-long pass filter set consisting of a 475AF40 excitation filter, a 505DRLP dichroic filter, and a 510ALP emission filter was used. The Zeiss Zen software version 2.3 was used to obtain microphotographs; the Fiji software (Image J) version 1.52 was used to process the images.

Analysis of QD-based hydrogels prepared using diamine derivatives of polyethylene glycol and using divalent cations by scanning electron microscopy Samples for scanning electron microscopy were prepared by placing 1 μl of hydrogel diluted tenfold on a porous silicon substrate and drying it for 48 h. The samples were analyzed using a MAIA3 scanning electron microscope (Tescan, Czech Republic) with a voltage of 5 kV. The Fiji software (Image J) version 1.52 was used for image processing.

Comparison of the fluorescence QY of QD-based hydrogels prepared using diamine derivatives of polyethylene glycol with different molecular weights

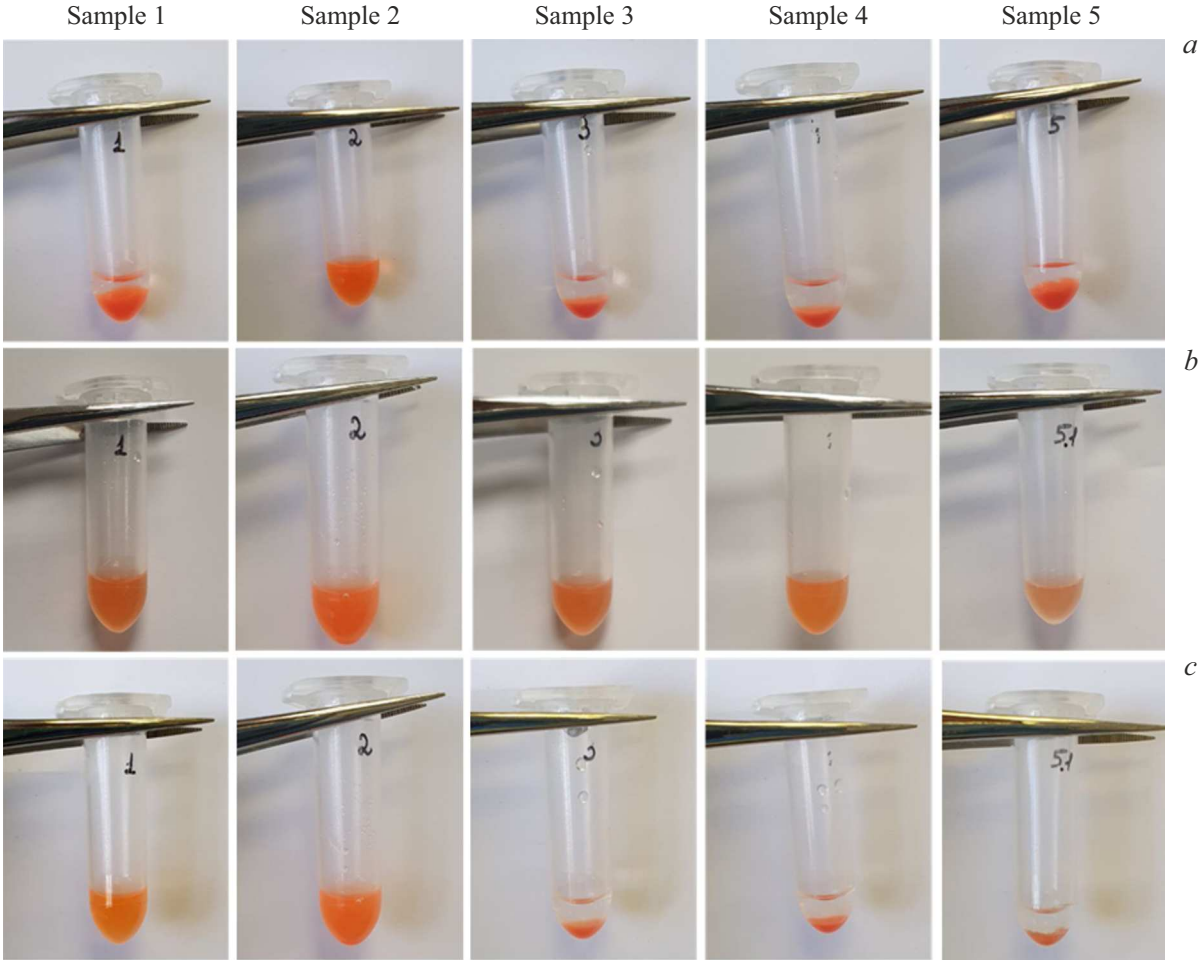

Figure 1. Photographs of control samples of CdSe/ZnS-Cys QDs with addition of 0.05 M MES, pH 6.0 (Sample 1) and diamino-PEG (Sample 2) and samples of gels obtained from CdSe/ZnS-Cys QDs using diamino-PEG (Sample 3, in two stages; Sample 4, in one stage) and divalent cations (Sample 5) (*a*) after 24 h of incubation, (*b*) after addition of 0.1 M NaOH (Sample 1, 3, 4) or 0.1 M EDTA (Sample 5), and (*c*) 24 h after the addition.

and using divalent cations Measurement of the fluorescence spectra of QDs and QD-based hydrogels prepared using diamino-PEG with different molecular weights was carried out using a Cary Eclipse spectrofluorimeter (Agilent) equipped with a fiber optic probe. To do this, 12.5 μl of a preliminarily prepared QD gel was applied onto a coverslip and incubated for 15 min to increase the viscosity of the sample. The fluorescence QY of the prepared samples was measured using an integrating sphere [18]. The sample was placed directly into the integrating sphere along the laser beam. In the measurements of the fluorescence QY of the QD-based hydrogels obtained using diamino-PEG, the source of excitation radiation was a semiconductor diode laser with an excitation wavelength of 398 nm (Taiko PDL M1 (PicoQuant)). The measurements were carried out in the pulse mode (100 kHz) at an average energy of the laser beam of 180 μW. To collect the fluorescence spectrum of the sample under study, an optical fiber was connected to the output port of the sphere, and an optical filter was mounted to suppress the laser radiation at the output. Thus, the optical fiber carried radiation only from the sample, the spectrum of which was accumulated by a portable Ocean Optics HR2000 + ES spectrometer.

Results and discussion

Development of an optimal method for preparing hydrogels based on CdSe/ZnS-Cys QDs and diamine derivatives of polyethylene glycol When 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC) and N-hydroxysuccinimide (NHS) were added to a solution of CdSe/ZnS-Cys QDs containing diamino-PEG with an average molecular weight of 2000 g/mol, the formation of hydrogels (Fig. 1, Samples 3 and 4) was observed. When divalent cations were added to the CdSe/ZnS-Cys QD solution according to a previously developed method [8], a hydrogel was also formed (Fig. 1, Sample 5). Analysis of the microscopy images of hydrogel Samples 3, 4, and 5 (Fig. 2) showed the presence of ordered structures consisting of CdSe/ZnS-Cys QDs, the structures being noticeably denser

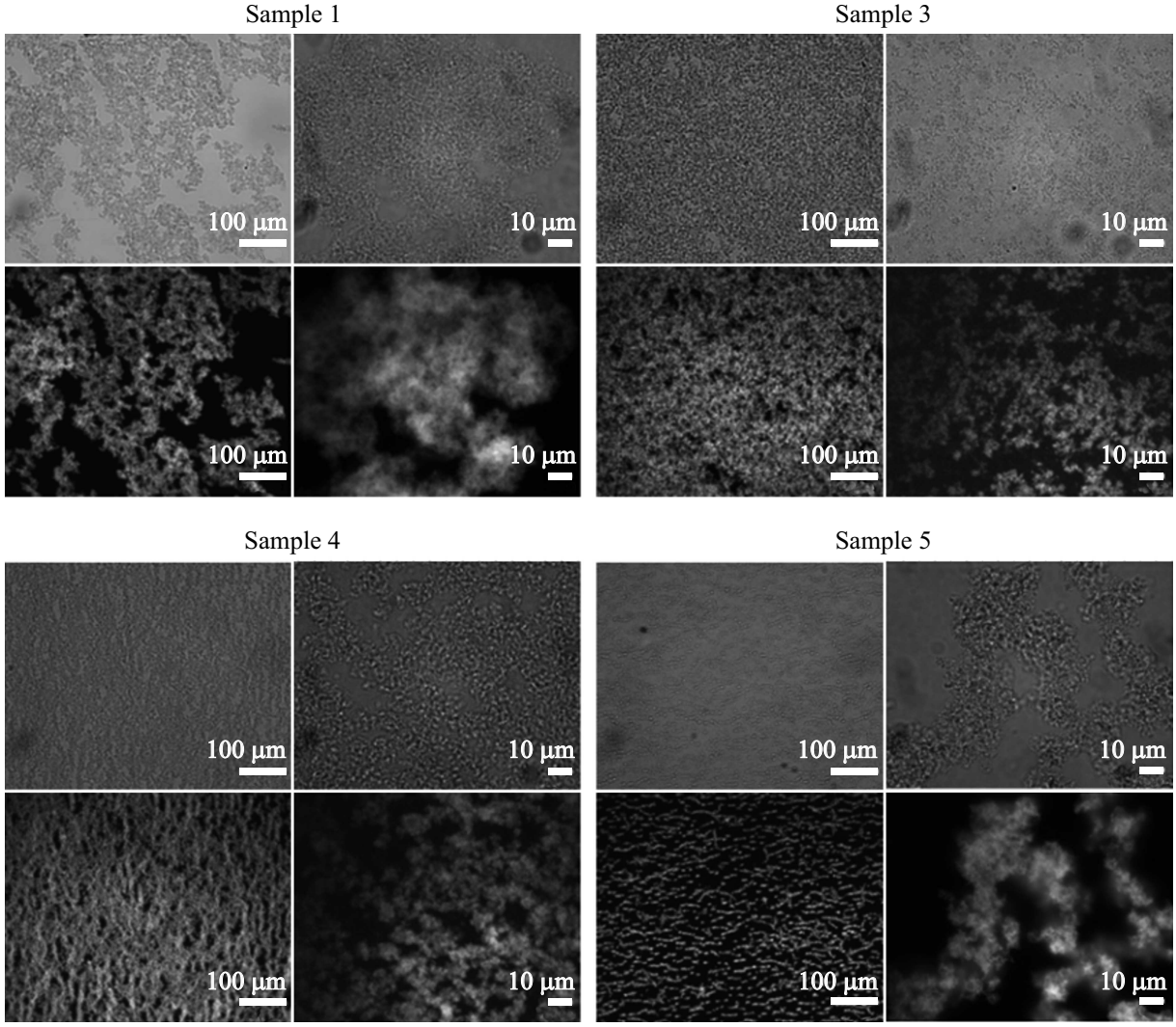

Figure 2. Microphotographs of control samples of CdSe/ZnS-Cys QDs with addition of 0.05 M MES (pH 6.0, Sample 1) and hydrogels obtained from CdSe/ZnS-Cys QDs using diamino-PEG (Sample 3, in two stages; Sample 4, in one stage) and divalent cations (Sample 5) after 24 h of incubation at magnifications of 200× and 1000× obtained using light (the top panel for each sample) and fluorescent (the bottom panel) microscopies after 24 h of incubation.

in hydrogel samples obtained using diamine derivatives of PEG (Samples 3 and 4) than in the gel sample obtained by adding $MgCl_2$ (Sample 5). In control Sample 1, when a 0.05 M MES buffer (pH 6.0) was added in a volume equivalent to the volume of the added solutions of EDC, NHS, and PEG, a QD precipitate was formed due to a decrease in the pH of the reaction medium when this buffer was added to a solution of QDs in 0.05 M borate buffer (pH 8.5). Analysis of this sample using optical microscopy demonstrated the presence of disordered structures in it, probably corresponding to QD aggregates. In control Sample 2, no gel or precipitate formed; therefore, micrographs of this sample are not presented.

The presented data show that we have developed a method for preparing hydrogels consisting of CdSe/ZnS-Cys QDs and diamino-PEG using a carbodiimide reaction in one or two stages. Comparison of the gels obtained using the described method with the gel obtained by adding divalent cations shows their denser structure, which can be explained by the formation of covalent bonds between linker molecules (PEG) and ligands on the surface of CdSe/ZnS-Cys QDs.

To assess the stability of the gels when the pH was increased to a value close to the pH of the initial QD solution (8.5–9.0), 50 μl of 0.1 M NaOH was added. In Sample 1, the precipitate that formed after 24 h of incubation had no ordered structure (Fig. 2), and when the initial pH of the mixture was restored, the QDs passed into solution (Figs. 1, *b*, 1, *c*). Analysis of Sample 1 24 h after the addition of the NaOH solution also showed the absence of ordered structures (Fig. 3). In the control sample, no changes were observed when NaOH solution was added. In experimental Samples 3 and 4, immediately after the

Table 2. Spectral characteristics and fluorescence QY of a solution of CdSe/ZnS-Cys QDs and of the samples of hydrogels from these nanocrystals obtained using diamine derivatives of PEG with different molecular weights and $MgCl_2$

Sample	fluorescence QY, %	Maximum wavelength of fluorescence, nm	Full width at half height or width, nm
QD CdSe/ZnS-Cys	35.0	595	29.7
Gel of QD + PEG3400	17.1	599	31.1
Gel of QD + PEG2000	25.0	599	0.7
Gel of QD + PEG400	22.8	601	30.4
Gel of QD + $MgCl_2$	17.2	601	31.3

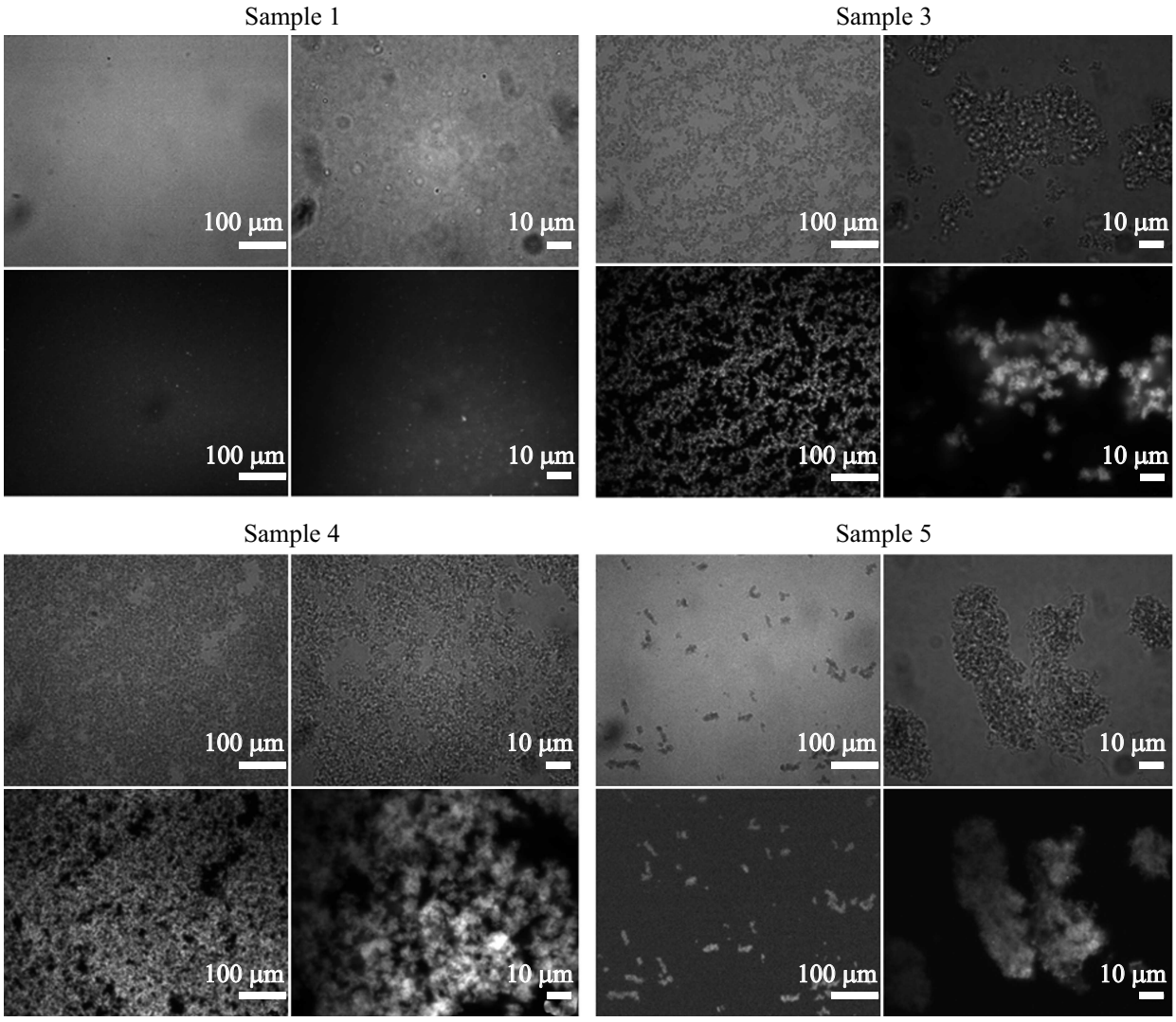

Figure 3. Microphotographs of control samples of CdSe/ZnS-Cys QDs with addition of 0.05 M MES (pH 6.0, Sample 1) and gels obtained from CdSe/ZnS-Cys QDs using diamino-PEG (Sample 3, in two stages; Sample 4, in one stage) after 24 h and divalent cations (Sample 5) 24 h after the addition of 0.1 M NaOH (Samples 1, 3, 4) or 0.1 M EDTA (Sample 5) at magnifications of 200× and 1000×, obtained using light (top panel for each sample) and fluorescence (bottom panel) microscopies.

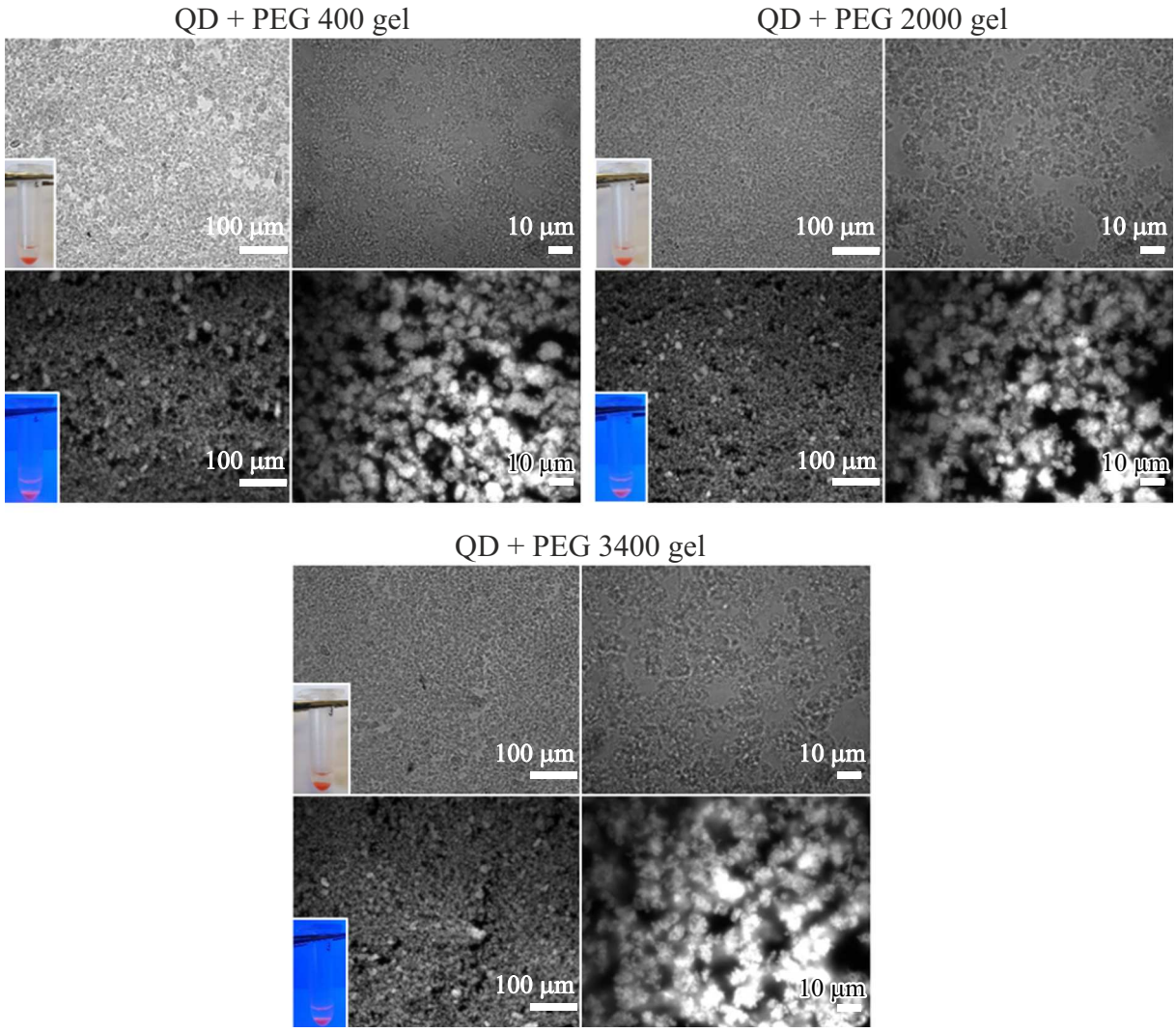

Figure 4. Microphotographs of hydrogels prepared from CdSe/ZnS-Cys QDs using diamino-PEG with molecular weights of 400, 2000, and 3400 g/mol after 24 h of incubation at magnifications of 200× and 1000×, obtained using light (the top panel for each sample) and fluorescent (the bottom panel) microscopies. The insets show the images of the gels under daylight and UV light.

addition of the NaOH there was resuspension of the gel, but after 24 h, the original gel was restored (Fig. 1).

Analysis of these samples using optical microscopy showed the presence of ordered structures, the structures identified in Sample 4 being denser than in those Sample 3 (Fig. 3). In Sample 5, after the addition of the EDTA solution, there was also resuspension of the gel, and after 24 h, there was the formation of a QD precipitate (Fig. 1), the analysis of which did not reveal ordered structures (Fig. 3).

Thus, the restoration of the structure of QD gels obtained using diamino-PEG after changing the pH of the solution indicates their strength due to the formation of covalent bonds between QDs and linker molecules via the carbodiimide reaction. In contrast, the formation of gels from QDs upon addition of divalent cations is reversible, since the addition of a complexing agent (EDTA) leads to the binding of divalent cations and destruction of the gel which is consistent with previously published results [6]. At the same time, comparison of Samples 3 and 4 showed that carrying out the conjugation reaction in one stage led to the formation of denser and more stable gels; therefore, this modification of the method was chosen for further study.

Comparison of hydrogels based on CdSe/ZnS-Cys QDs obtained using diamine derivatives of polyethylene glycol with different molecular weights

To compare the structures of hydrogels based on CdSe/ZnS-Cys QDs containing diamino-PEG with molecular weights of 400, 2000, and 3400 g/mol, we used the optimal ratios of reagents and reaction conditions established in previous experiments. Analysis of the obtained hydrogel samples using light and fluorescent microscopies demonstrated the presence of ordered structures in all the samples (Fig. 4). However, when diamino-PEG with a lower

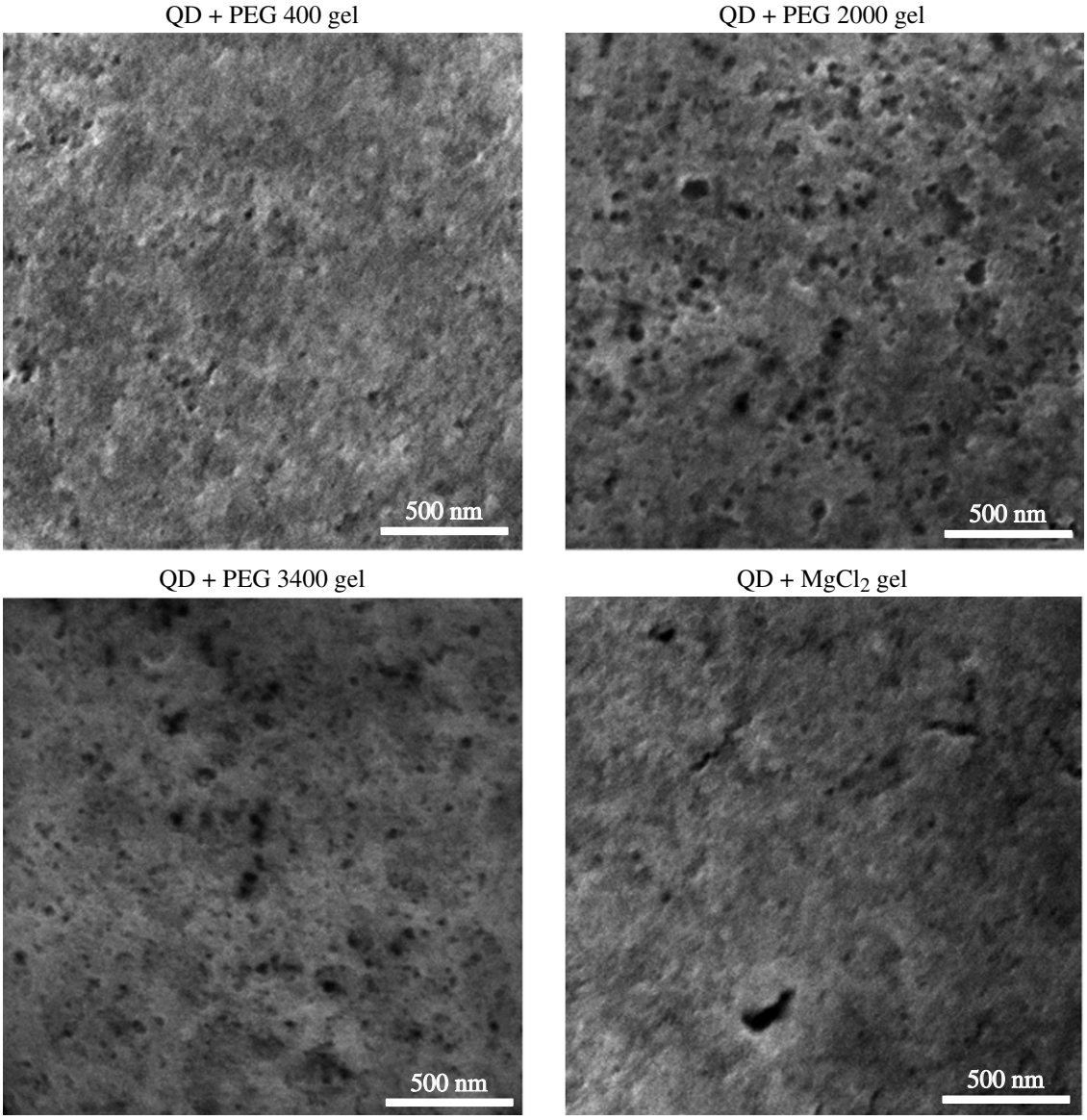

Figure 5. Microphotographs of gels prepared from CdSe/ZnS-Cys QDs using diamino-PEG with molecular weights of 400, 2000, and 3400 g/mol and $MgCl_2$.

molecular weight was used, the obtained hydrogels had less granularity, which may have been due to the formation of denser structures with a decrease in the length of the linker molecule.

Analysis of the obtained hydrogels by scanning electron microscopy showed that hydrogels based on CdSe/ZnS-Cys QDs obtained using diamino-PEG with different molecular weights had considerable structural differences (Fig. 5). The QD hydrogel prepared using the PEG derivative with the lowest molecular weight (400 g/mol) had significantly smaller pores than the gels prepared using PEG with molecular weights of 2000 and 3400 g/mol. According to the analysis of micrographs obtained by SEM, the CdSe/ZnS-Cys QD gel formed as a result of the addition of divalent cations ($MgCl_2$) had a less ordered structure than gels obtained using PEG.

Thus, the method of preparing gels from QDs using diamine derivatives of PEG leads to the formation of porous structures, and by using PEG with different molecular weights, gels with different pore sizes can be obtained.

Comparison of fluorescence QYs of the gels based on CdSe/ZnS-Cys QDs obtained using diamine derivatives of polyethylene glycol with different molecular weights and divalent cations with solubilized QDs CdSe/ZnS-Cys QDs from a 0.1 M NaOH solution had a fluorescence QY of 35%. Figure 6 shows the fluorescence spectra of solutions of CdSe/ZnS-Cys QDs, as well as samples of QD gels obtained using diamino-PEG with molecular weights of 400, 2000, and 3400 g/mol and divalent cations ($MgCl_2$).

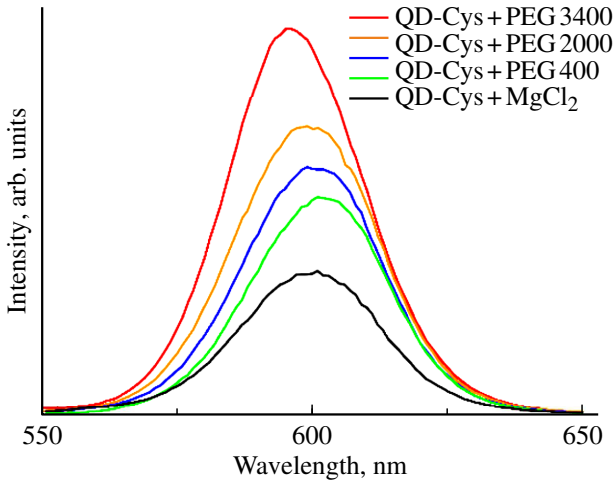

Figure 6. Spectra of QD-based gels prepared using diamino-PEG with different molecular weights.

The obtained results show a shift of the fluorescence peak to the red region of the spectrum by 4–6 nm for samples of CdSe/ZnS-Cys QD hydrogels containing diamino-PEG compared to the maximum fluorescence emission wavelength of the CdSe/ZnS-Cys QD solution. A slight broadening of the spectra of hydrogels based on CdSe/ZnS-Cys QDs containing diamino-PEG (by 0.7–1.6 nm) compared to the spectrum of a solution of CdSe/ZnS-Cys QDs is also noticeable. Nevertheless, the broadening and shift of the spectrum to the red region indicate a decrease in the distances between QDs in the gel with a decrease in the molecular weight of the diamino-PEG polymer, which suggests nonradiative energy transfer in the systems under study [19].

Table 2 presents the spectral characteristics and the QYs of fluorescence of CdSe/ZnS-Cys QDs in solution and in hydrogel samples obtained using PEG and divalent cations.

In the process of formation of hydrogels based on CdSe/ZnS-Cys QDs using diamine derivatives of PEG and divalent cations, there is a decrease in the fluorescence QY in the range from 28 to 50%. In such a complex system as hydrogels, achieving a high fluorescence QY as a result of gelation does not seem to be an easy task; therefore, the obtained QYs can be regarded as good. Note that hydrogels obtained using diamine derivatives of PEG with molecular weights of 400 and 2000 g/mol have a higher fluorescence QY compared to gels obtained by the standard method using divalent cations, and the fluorescence QY of hydrogels obtained using PEG with a molecular weight of 3400 g/mol is very close to the QYs of these hydrogels.

Conclusion

Thus, a method for preparing hydrogels based on CdSe/ZnS QDs modified with cysteine using diamine derivatives of polyethylene glycol has been developed and optimized, and these hydrogels have been compared with hydrogels obtained using the standard method of divalent cation addition.

The dependence of the structure and morphology of the obtained gels on the average molecular weight of diamine derivatives of PEG used to obtain the hydrogels has been analyzed, and the relationship between the molecular weight of PEG and the porosity of the hydrogel has been shown, which opens up the possibility of developing hydrogels with a controlled structure and specified optical properties.

In addition, we have demonstrated a less pronounced decrease in fluorescence QY for gels obtained using diamino-PEG with molecular weights of 400 and 2000 g/mol than for the gels obtained using diamino-PEG with a molecular weight of 3400 g/mol and divalent cations.

These results will be used to design sensor systems based on gels obtained from CdSe/ZnS QDs and diamine derivatives of polyethylene glycol.

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Conflict of interest

The authors declare that they have no conflict of interest.

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